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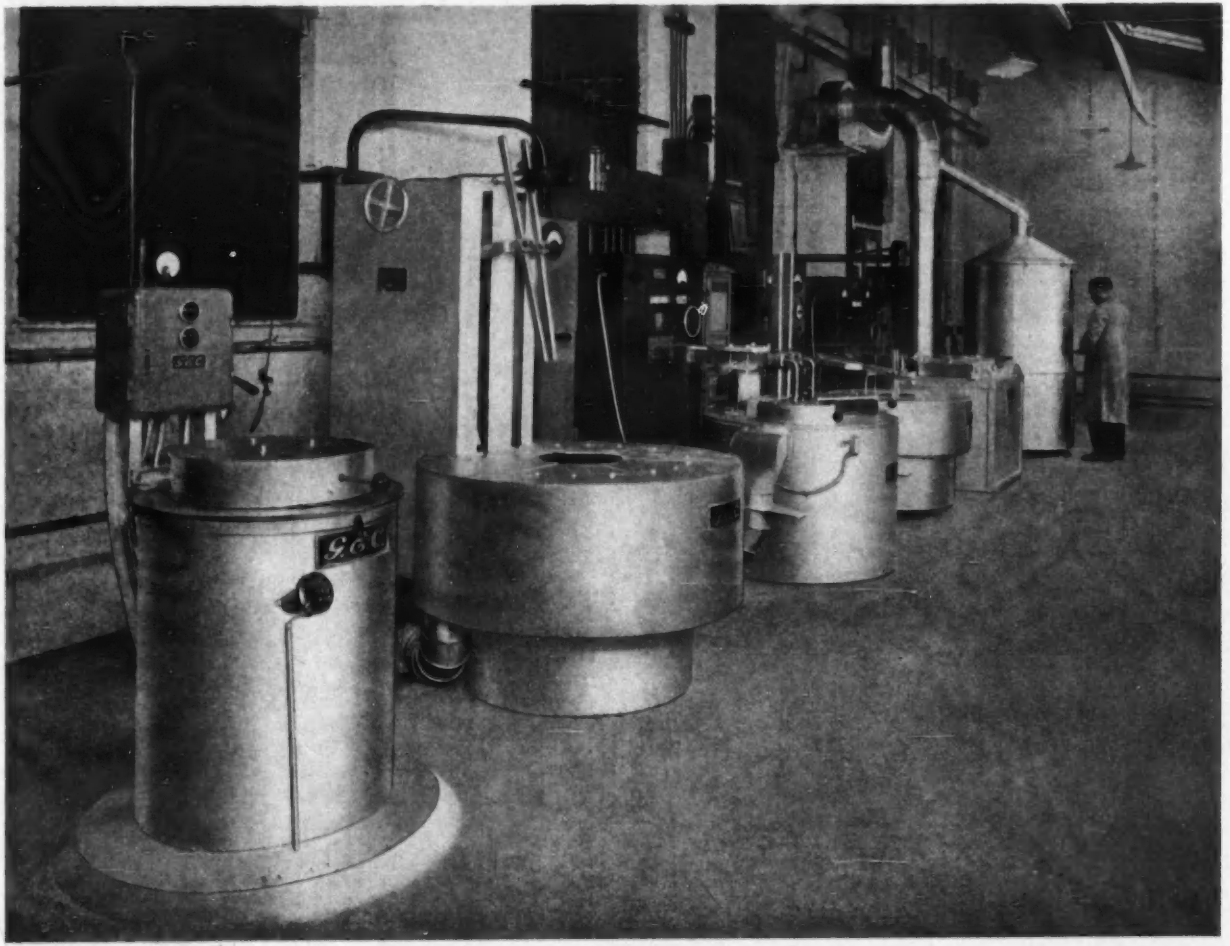


A MODERN TOOL ROOM HEAT TREATMENT SHOP.

View in a large engineering works, showing a range of G.E.C. electrode type salt bath and forced air circulation furnaces for the preheating, hardening, hot quenching, carburising and tempering of tools.

Powder Metallurgy.

By S. V. WILLIAMS, B.Sc.

G.E.C. Research Laboratories.

1. INTRODUCTION.

POWDER metallurgy is the production of metal parts from powders by moulding and sintering processes. A more comprehensive definition is that of the American Society for Metals which states that "Powder metallurgy is the art of producing metal powders and shaped objects from individual, mixed or alloyed metal powders, with or without the inclusion of non-metallic constituents, by pressing or forming objects which are simultaneously or subsequently heated to produce a coalesced, sintered, alloyed, brazed or welded mass, characterised by the absence of fusion or the fusion of a minor constituent only."

The subject is one which has received considerable notice in the technical press during the last few years and there may be some tendency to suggest that the technique is of recent origin whereas this is not so, although it is true that the application of the process for the large scale production of parts for general engineering purposes is a comparatively recent development. There is evidence that the process was used in ancient times for the production of precious metals and also iron in massive form. Also, over 100 years ago Wollaston used powder metallurgy for the production of platinum.

The use of the process, on what may be described as a commercial scale, dates back to the beginning of the present century and it is interesting to note that many of the early developments were closely associated with the electrical industry. The search for a satisfactory incandescent lamp filament was solved in 1909 by Coolidge who discovered the method for producing ductile wire from tungsten powder. This method embodied all the fundamentals of present day powder metallurgy and included considerations associated with the original powder, pressing and sintering. The electrical industry rapidly took advantage of the process for the production of other refractory metals and their alloys which are particularly useful for components such as contacts and electrodes. In all these instances, however, the total quantity of metal involved was not large and the process was regarded as something special and outside the field of the ordinary metallurgist.

Further interest was focused on the subject by the development of cemented tungsten carbides. Although originally developed by the electrical industry for wire drawing dies, they were later used on an increasing scale for cutting tools by the engineering industry generally. From this stage onwards developments have been rapid and include the production of porous bronze and porous iron bearings and of iron and various alloy parts which were previously made by conventional methods such as casting, forging and machining. As far as these later developments are concerned America is probably ahead of other countries, but although precise information is not available it would appear that in both Russia and Germany, powder metallurgy is used on a fairly extensive scale. In this country there can be no doubt that the war has interfered with developments in this field, but that the subject has not been entirely ignored is indicated by the fact that the first book dealing with the subject in general, was that by W. D. Jones[1] published in England in 1937. As an indication of the rapid progress made during the last few years it is interesting to compare Jones' book with that edited by Wulff[2] in America in 1942. The latter is a collection of papers presented at the Conferences on Powder Metallurgy held at the Massachusetts Institute of Technology in 1940 and 1941 respectively.

View in a large engineering works, showing a range of G.E.C. electrode type salt bath and forced air circulation furnaces for the preheating, hardening, hot quenching, carburising and tempering of tools.

2. APPLICATION OF POWDER METALLURGY.

Parts made by powder metallurgy may conveniently be divided into two main groups.

(*a*) Parts which cannot be produced by conventional metallurgical processes such as casting, forging and machining, etc.

(*b*) Parts for which powder metallurgy offers some technical or economic advantage over other production processes.

In the few examples mentioned, the process is such that the finished parts have no porosity. There is, however, a very important field in which advantage is taken of powder metallurgy to produce parts with a definite and controlled porosity. These include the well-known porous bearing materials which probably represent the largest single type of application for which powder metallurgy is used at the moment. They are made either of

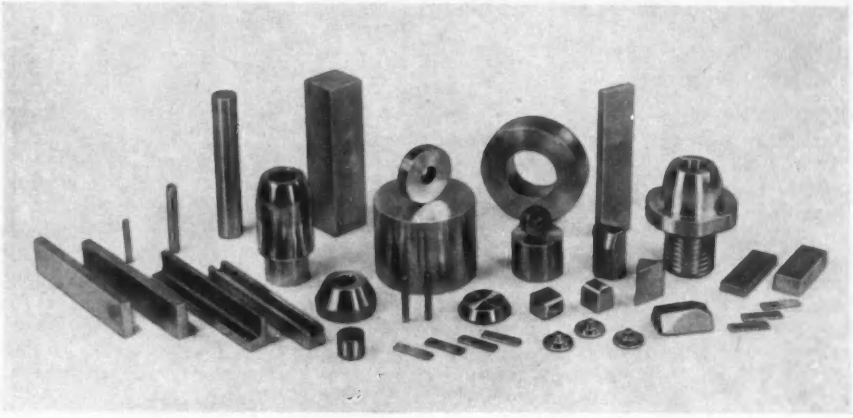


Fig. 1. Group of tungsten-copper (Copelmet) and tungsten-silver (Silvelmet) contacts and electrodes.

Most of the early applications of the process such as for the production of tungsten, molybdenum and their alloys come in the first group. Similarly the production of the hard metals or cemented carbides used for wire drawing dies and cutting tools is only possible by powder metallurgy. In these, tungsten and other carbides are bonded or cemented together by a metal of lower melting point, usually nickel or cobalt. As their name implies, these metals are very hard and consequently difficult to machine, but one of the advantages of powder metallurgy is that parts can be made to finished dimensions, hence the problem of machining hard metals does not arise. Similar in many respects to cemented carbides is G.E.C. Heavy Alloy which is also a powder metallurgy product. Its manufacture and properties have been described in a previous issue of this Journal.[3] It contains about 90 per cent tungsten and has many important applications in various branches of engineering on account of its high density (16·5—17 gms/cc.) and good arc resisting properties.

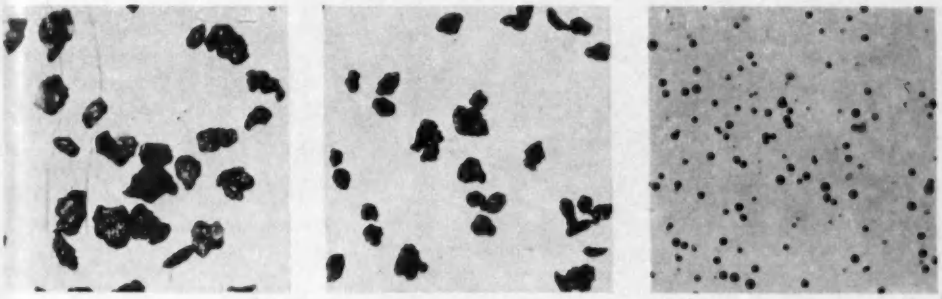
bronze or mainly of iron, typical compositions being respectively 90 per cent copper, 10 per cent tin, and 73·5 per cent iron, 25 per cent copper, 1·5 per cent graphite. Bearings of the compositions mentioned are capable of carrying loads of 6,000 and 60,000 lbs./sq. inch respectively. It is usual to mix the individual powders and so control the sintering that the final product, which is true to size, will absorb up to 35 per cent of its own volume of oil. Originally made in small sizes, it is reported that in America porous bearings up to ½ cwt. in weight are in regular production.

Powder metallurgy is also the only method of making parts of certain mixtures of metals and non-metals and of metals which do not alloy. Typical examples in this field are diamond-impregnated grinding wheels and various mixtures of tungsten or molybdenum with copper or silver. Mixtures of these metals combine the useful properties of the individual constituents. Thus tungsten-copper mixtures have the good arc-resisting properties due to the tungsten, coupled with good electrical

conductivity due to the copper. The proportions of the individual metals in this and other similar mixtures may be varied over a wide range according to the subsequent use of the part in question. Copper-tungsten and silver-tungsten electrodes made by powder metallurgy are shown in fig. 1.

Of the second group of powder metallurgy products, an outstanding example is the Alnico permanent magnet. Alnico—which is an alloy of aluminium, nickel, cobalt and iron—can be made by casting, but the material is very hard and brittle and consequently difficult to machine. By the powder technique, however, Alnico magnets can be made to the exact dimensions required without any final machining. This is particularly useful in the case of the smaller size magnets which are difficult to make by the casting process. In addition, Alnico made from powders is more uniform and free from defects such as blowholes and segregation which are difficult to avoid in the cast material. Thus Alnico is an example for which powder metallurgy offers technical advantages over the casting method of production.

There is, however, a large variety of parts which can be made without much difficulty by conventional production processes but for which powder metallurgy offers considerable advantages. These are essentially economic in so far that, with small and fairly simple parts in particular, very high production rates are possible and at the same time material, which would otherwise be wasted due to machining, is saved. Small gear wheels are a very good example of this type of product, since up to 50 per cent of metal has to be removed when they are made by machining from bar stock or castings. This type of product has been made in very large quantities in America and it is claimed that it is possible to produce gear wheels with equally if not more accurate tooth profiles by powder metallurgy than by the more usual methods. In some cases the close tolerances of the final products are only obtained by a coining or cold pressing operation after sintering. The process is not confined to any particular metal or group of metals but embraces the ferrous and non-ferrous metals and alloys including the light metals and their alloys.



Electrolytic (x60) Reduced oxide (x60) Carbonyl (x100)

Figs. 2, 3 and 4. Photomicrographs of iron powders produced by different methods.

3. PRODUCTION OF METAL POWDERS.

Metal powders are used for a variety of purposes other than powder metallurgy and there is an extensive literature on the subject generally. A detailed discussion of the various methods used is outside the scope of this article, but since the metal powders from which the parts are produced are obviously of fundamental importance, a brief reference to the more important methods will be made. It will be appreciated that it is possible to produce a particular metal powder by a number of different processes and that the choice of one or the other for any particular job will be determined by such factors as the chemical and physical properties of the powder, raw material supplies and, in many instances, economic considerations.

(*a*) *Milling or Comminution* of the solid metal or alloy is particularly suitable for brittle materials although special grinding mills capable of reducing malleable metals to powder have been developed and are used. An interesting and recent application of this method of powder production is the crushing of metal scrap such as steel turnings, cast

iron borings and non-ferrous metal swarf.

(*b*) *Reduction of metallic oxides* is probably the process in most general use for the production of powders used in powder metallurgy. The reducing agent is usually hydrogen or a hydrogen-containing gas or carbon. By suitable control of the preparation of the oxide and the reduction conditions, it is possible to produce metal powders to a close specification as regards chemical purity and physical properties such as grain size. An example in which very accurate control is exercised is the production of tungsten used in the lamp industry, by the reduction of tungsten oxide by hydrogen. Considerably larger quantities, however, of commercial quality tungsten powder are produced by the reduction of the oxide by carbon. Similarly iron powder is produced by the two methods.

(*c*) *Electrolytic deposition* is used on a commercial scale for the production of iron and copper powders. It can also be used for other metals and for certain alloys. It is possible to produce high purity metal powders by this process.

(*d*) *Decomposition of gaseous compounds* is of interest because it is the method in commercial use for the large scale production of iron and nickel powders by the Mond Carbonyl process. The powders produced by the decomposition of metal carbonyls are spherical in contrast to those produced by, say, the electrolytic process which have a dendritic or tree-like structure. Other gaseous compounds can be used for the production of metal powders but these are mainly of academic interest.

(*e*) Other powder producing processes include atomization (spraying), condensation of metal vapours, shotting, granulation and machining.

In all the processes mentioned above it is possible to exercise some measure of control and produce powders having different chemical and physical characteristics which have an important influence as far as their subsequent use in powder metallurgy is concerned. Figs. 2, 3 and 4 show photomicrographs of iron powders produced by three of the processes to which reference has been made.

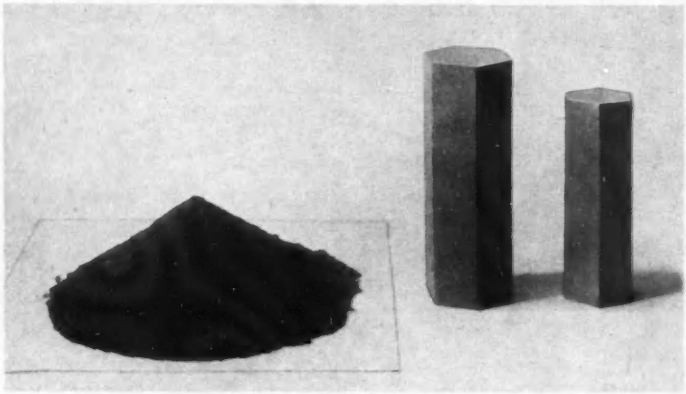


Fig. 5. Fundamental stages in the production of parts by powder metallurgy: powder, pressed compact and sintered part.

4. PRODUCTION PROCESSES.

There are a number of variations in the sequence of operations used in powder metallurgy, but fundamentally the process consists of pressing the metal powder to shape in a suitable die followed by heating or sintering the pressed compact in order to bond or coalesce the particles of metal powder. The fundamental stages in the process are illustrated in fig. 5.

(*a*) *Powder preparation.*

The characteristics of the metal powders largely determine their behaviour during the subsequent processing and the suitability of a powder for any particular job is a matter for experiment. Having obtained powder of suitable quality it is sometimes an advantage to anneal the material prior to pressing. In some instances it is also advantageous to mix with the powder a small quantity of lubricant or binding agent. This mixing must be

thorough and uniform. Similarly the mixing of the constituent metals when making alloys is of vital importance in order to ensure homogeneity in the final product.

(*b*) *Pressing* may be done either cold or hot although at the present time cold pressing is the method in more general use. The presses used are of the mechanical or hydraulic type, the former being used for the mass production of small parts at comparatively low pressures. For parts requiring high pressures hydraulic presses are used. The actual pressure may range from 1 or 2 tons to over 100 tons per sq. inch, some typical examples being Heavy Alloy 5 tons, certain iron parts 25—30 tons, Alnico 90—100 tons/sq. inch. With higher pressures difficulties with dies increase and consequently every effort is made to work with the lowest pressure consistent with the properties required in the final product. Die design is of paramount importance. It can be taken that metal powders do not flow like liquids and will not fill up odd corners in the die during the pressing operation. This imposes certain limitations on the variety of shapes that can be produced readily. However, by exercising ingenuity in die design, such as providing multiple plungers which come into operation at the appropriate moment, it is possible to press intricate shapes, although it will be appreciated that the cost of such dies is high and only justified in the case of large scale production. The pressure to a certain extent governs the shrinkage of the pressed compact during sintering, from which it follows that the pressure applied should be uniform, otherwise the shrinkage will be non-uniform with the result that the sintered part will be distorted. It is possible to design the die to allow for slight variations in pressure and it is also possible to correct distortion of the sintered part, but even so there are limits to what can be done in these directions and it is obviously better to design the die so that the pressure is uniform. It is difficult to transmit pressure through any great depth of powder and with parts that are much deeper than they are wide it is customary to use dies with top and bottom plungers which operate simultaneously. Finally, it should be remembered that the present design of certain small parts is to a certain extent determined by existing production processes and, as powder metallurgy is developed, parts will be designed so as to take advantage of the possibilities of the new production process.

Lubrication is an important factor in pressing, and, as already mentioned, the lubricant may be incorporated with the powder or alternatively may be applied to the inside of the die. By a suitable choice of lubricant the extraction of the pressed compact from the die is facilitated and, what is of equal importance, the wear of die, particularly by abrasive powders, is reduced.

Apart from what may be called the conventional method of producing powder compacts by cold pressing, other processes which are used on a limited scale include extrusion, centrifuging and vibration.

With hot pressing many difficulties are encountered. In particular, die design presents many more problems than in the case of cold pressing. Also with many powders precautions have to be taken to avoid oxidation. These and other difficulties have in certain instances been overcome, but even so hot pressing of metal powders is not as yet used to any great extent on a commercial scale. Technically, hot pressing has certain advantages in so far that it combines pressing and sintering in one operation, and, with some metals and alloys, permits the production of fully dense material more readily than is possible with the more usual two stage process. Even so, these advantages are more than offset by the difficulties associated with the process, and so far it has not found very general application.

(*c*) *Shaping* of the pressed compacts, either before or after a preliminary heating to some temperature below the normal sintering temperature, is not usually included in the normal sequence of operations for parts produced on a large scale. It is, however, very useful in the production of a small number of parts which do not justify a special die. In these cases it is possible to press a part in an existing die of approximately the required shape and machine before sintering. At this stage the compact is relatively soft and readily machined and consequently shaping after pressing is frequently employed for the production of such parts as special tungsten carbide tool bits, Alnico magnets and Heavy Alloy. Machining at this stage has an additional advantage in that the material removed can easily be crushed to powder and used again.

(*d*) *Sintering* is the process of heating the cold pressed compact in order to bring about bonding, coalescence and in many cases true alloying of the particles of powder. During sintering, a portion of the compact may be molten for part or the whole of the time that the compact is at temperature, but in all cases the sintering temperature is lower than the melting point of the mass as a whole. Sintering

temperatures vary over a wide range from a few hundred degrees for some of the non-ferrous metals to over 3000 degs. C. for tungsten. In the majority of cases sintering is carried out in a non-oxidising and usually a reducing atmosphere. Hydrogen, cracked ammonia or partially burnt town's gas[4] are generally used, the choice to a certain extent being determined by the metal or alloy being

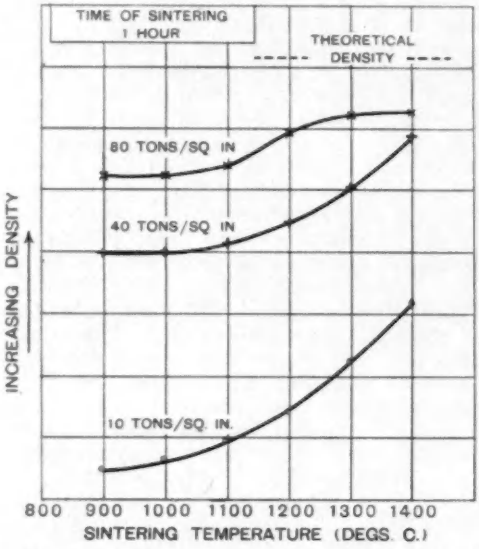


Fig. 6. Effect of sintering temperature on the density of iron compacts pressed at various pressures.

sintered. Sometimes sintering is associated with processes such as carburising or nitriding in which case the appropriate atmosphere is used. Heating is usually done in electric resistance furnaces of the continuous or batch type. Induction heating is used on a limited scale and is likely to find greater application in the future. In the case of tungsten and molybdenum the pressed bars of metal are sintered by passing a current through the bar which is held between contact clips so designed that the shrinkage of the bar is accommodated.

The changes that take place during sintering depend on a number of factors such as the presence or absence of a liquid phase, type of powder used, pressure, temperature and time of sintering.

Thus with a simple metal such as iron, for any particular powder and with constant sintering conditions, the higher the compacting pressure the lower the porosity after sintering. On the other hand with a fixed compacting pressure the degree of porosity will vary according to the temperature, and to a lesser degree the time, of sintering. An indication of the inter-relationship of these factors is shown in fig. 6.

However, when a liquid phase is present, somewhat different results may be obtained. Fig. 7 shows the density/sintering temperature relationship for an alloy containing 10 per cent nickel, 90 per cent tungsten. In contrast with the curves for iron, which show a progressive increase in density with increasing sintering temperature, the density of the nickel-tungsten alloy increases suddenly at about 1450 degs. C. which corresponds with the melting point of the nickel phase.

Other examples of powder metallurgy products which have a liquid phase present during sintering are Alnico and the cemented carbides.

One feature of the alloys which are partially molten during sintering is that it is possible to attain the theoretical density with comparatively short sintering times. In the absence of a liquid phase this result is obtained only by the use of high pressures and/or very prolonged sintering times. In many cases, however, apart from those for which the pressure and sintering is controlled so as to produce a predetermined degree of porosity such as in porous bearings, any residual porosity is often of no particular significance in so far that the parts will have more than sufficient strength for the purpose required.

(*e*) *Finishing Processes* are those which are applied to the sintered part. Thus parts which are required to very close dimensional limits are often coined or hot pressed. Such processes may also be designed to reduce or eliminate any residual porosity or to correct any slight distortion of the part in question. On the other hand, the sintered product is sometimes the ingot, which has been produced by powder metallurgy, and which is then worked down into sheet or wire by the usual rolling and drawing techniques. The production of tungsten wire by these methods has already been referred to. This and similar examples, however, may be regarded as somewhat special applications of powder metallurgy, and in the more general application of the process, the object is to produce the final article with the minimum of finishing operations.

In the case of porous bronze bearings and the like, the sintered parts are finally impregnated with oil, but this and kindred

operations are non-metallurgical aspects of powder metallurgy.

5. CONCLUSIONS.

An attempt has been made to give a general picture of powder metallurgy and to indicate

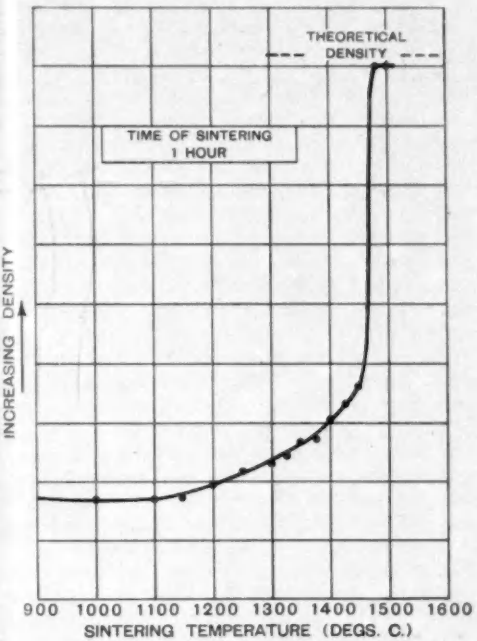

THEORETICAL DENSITY
TIME OF SINTERING 1 HOUR
INCREASING DENSITY
900 1000 1100 1200 1300 1400 1500 1600
SINTERING TEMPERATURE (DEGS. C.)

Fig. 7. Effect of sintering temperature on the density of a 10 per cent nickel 90 per cent tungsten alloy.

the directions in which the process can be applied with advantage. It will be appreciated that the precise production conditions for any particular metal or alloy can only be determined by experiment and, once established, it is essential that they should be accurately controlled, otherwise variations in the finished product will occur. Control of the properties of the original powder, as regards both physical and chemical properties, is particularly important.

For products which can only be made by powder metallurgy, the cost of the original powders is of secondary importance. For those in which the process is an alternative to existing methods of production, the cost of the original powders is of importance in so far that the economy of adopting a powder metallurgy production process may be related directly to this factor. From what has been said it is apparent that powder metallurgy is well adapted to the production of small parts, and although reports from America indicate that quite large parts are being produced, it will be appreciated that the larger the part being made the greater the difficulties associated with dies and presses, etc. All these factors, however, can be evaluated, and in cases where a large number of parts is called for or when the part in question can only be made by powder metallurgy, considerable expenditure on dies, presses, furnaces and other equipment can be justified. Consideration of such factors as these, in some measure accounts for the apparent lack of interest in this country in powder metallurgy. But although we cannot claim the spectacular advances that have undoubtedly been made in America, there are certain important applications in use at the present time which, for reasons of security, cannot be disclosed; but there can be no doubt that many people in this country are fully alive to the possibilities of powder metallurgy which is already being used to a greater extent than is generally appreciated.

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The Application of Radiant and Inductive Heating to Industrial Processes.

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I. INTRODUCTION.

HEATING is used at one stage or another in a wide range of industrial processes for purposes varying from the promotion of physical changes, such as expansion, softening, melting and evaporation to the acceleration of chemical reactions. The selection of the method of heating most suited to any particular process is a matter requiring a knowledge of the characteristics both of the process and of the methods of heating which are available. Until recently, conduction and convection were the most widely used methods of heat transfer. Usually, they produced the desired effect in the finished product, but in many cases they were slow and were by no means the most suitable ways of achieving this object. During the last few years, the rapidly increasing demands for materials for war production purposes have led to demands for economy in heating time and for a reduction in the amount of floor-space occupied by heating equipment. These in turn have led to a reconsideration of existing practice and to the introduction of alternative methods, chief among which are Radiant Heating and Induction Heating. The characteristics of the various methods of heating are discussed in general terms in the next section and the newer methods are considered in greater detail in the sections which follow.

II. HEATING METHODS.

The three methods of transferring heat from an object at a higher temperature to another at a lower temperature are by conduction, convection and radiation. For transfer to take place by conduction, the source of heat must be in contact with the object being heated. Thus the applications where this method of transfer may be employed are usually those in which the surface of the object is of simple shape (*e.g.*, where it is flat and may be heated by contact with a flat surface or with a heated roller). For applications such as these, conduction transfer is usually very satisfactory provided the thermal conductivity of the object is sufficient to give the necessary degree of temperature uniformity throughout its mass.

An object is said to be heated by convection when heat is imparted to it through the motion of a heated liquid or gas to which it is exposed. When this motion is brought about by local variations in the density of the fluid (caused by contact with the cool surface of the object) and by gravitational forces, the heat transfer is said to be by natural convection. When the motion is caused by some external means—for example, a fan, in the case of a gas, or a pump in the case of a liquid—transfer is said to be by forced convection. Ovens relying largely on heat transfer by natural convection with air as the heating medium are used extensively, but suffer from the drawback that it takes a long time for an object to reach air temperature. Rates of heating with both natural and forced convection are considered in greater detail in a later section.

Thermal radiation (or radiant heat) is the name given to energy which a body emits by virtue of its temperature, and it may be regarded as being transmitted through space in the form of electro-magnetic waves or as energy quanta. The nature of the radiation emitted depends on the temperature of the source. Thus the radiation emitted by a source at a temperature of 500 degs. C. is all in the infra-red region of the spectrum, whilst a source at a temperature of 2500 degs. C. emits an appreciable amount of visible light as well as infra-red rays. Visible light and infra-red radiation differ in wavelength, but in other respects they are very similar; both travel through space at the same velocity and both are capable of being reflected, refracted

or absorbed at a surface. A body heats when it absorbs radiation but is not affected by any radiation which it reflects or transmits. If absorption takes place at the surface, heat is generated there, and any heating effect elsewhere is due to conduction from the surface. Conversely, if a body is semi-transparent, radiation is absorbed at and below the surface and heat is generated throughout the mass of the material. In most cases, heat is generated at the surface, semi-transparent materials being in the minority. One of the chief advantages of radiant heating is that with suitably designed equipment, very rapid rates of heat transfer are attainable.

Induction heating differs from the processes just described in that it is not a method of *heat transfer*. Instead, heat is generated by electrical means inside the material being treated. Two distinct methods of application are involved. In the first, the material is made the dielectric of a condenser, the plates of which are connected to a source of radio-frequency power. Heating is brought about by losses occurring in the dielectric, and provided the material is homogeneous and there are no heat losses from the surface, the rate of temperature rise is uniform throughout. This method is particularly suited to processes in which a considerable thickness of a thermal insulator must be heated uniformly and to applications in which a thinner layer of such a material requires both uniform and very rapid heating.

The second method of application may be used with materials which are better electrical conductors. Current at a frequency which may be anything between ordinary mains frequency and radio frequency is passed through a coil which is linked with the body to be heated and a current is induced in the latter. This causes it to heat up and in suitable circumstances extremely rapid rates of heating may be obtained.

There is at present no established terminology for describing and differentiating between these two methods. The terms "Radiothermics" and "Electronic Heating" have been used in America for both of them, while "Heatronic Moulding" and "Chemotronics" have been used for special applications. In this article, the first method (in which the material undergoing treatment is the dielectric of a condenser) will be referred to as "Capacity Current Heating," and the second (in which it is placed in an alternating magnetic field) will be referred to as "Eddy Current Heating."

III. HEAT TRANSFER BY CONVECTION.

In order fully to appreciate the advantages which radiant heating has to offer, it is necessary to consider the characteristics of convective heating, the system which, in most instances, it will be called on to replace.

The variables which have to be taken into consideration in any theoretical treatment of the subject of convective transfer include the size, shape, orientation and temperature of the body being heated and the velocity, conductivity, density, specific heat, viscosity, expansion coefficient and temperature of the fluid. The subject is complex, and comprehensive data are available only for some of the simpler shapes such as cylinders with axes vertical and horizontal, and flat sheets.[1]

The rate of heat transfer (or, strictly speaking, energy transfer) to a body at temperature t_1 degs. C. in air at t_2 degs. C. by natural convection may be represented by the formula :—

$$H = C\,(t_2 - t_1)^n \text{ watts/sq. ft.} \quad \cdot \quad \cdot \quad \cdot \quad (1)$$

Where C, the coefficient of natural convection, and n vary with the size, shape and orientation of the body. For horizontal cylinders above 1 inch in diameter, C and n remain fairly constant, but for fine wires, C increases to as much as 50 times its value for

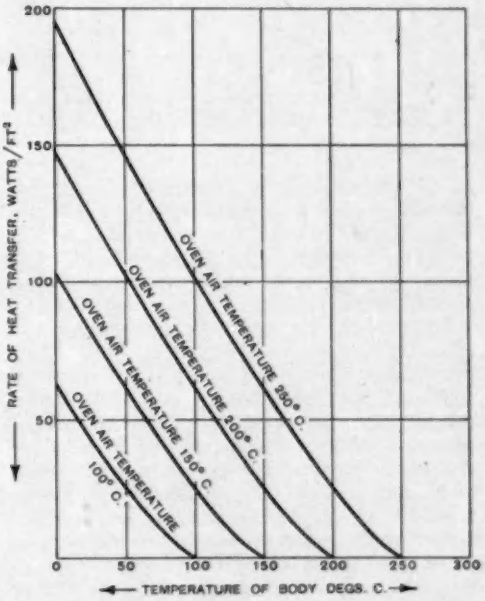

Fig. 1.—Variation of rate of heat transfer to a body by natural convection with body temperature.

large cylinders, whilst n decreases from about 1·3 for large cylinders, to just over 1 for fine wires. For large bodies having about the same surface area facing upwards as downwards (*e.g.*, cylinders 6 ins. or more in diameter and flat sheets) the formula may be written :—

$$H = 0{\cdot}196\ (t_2 - t_1)^{5/4} \text{ watts/sq.ft.} \quad \cdot \quad (2)$$

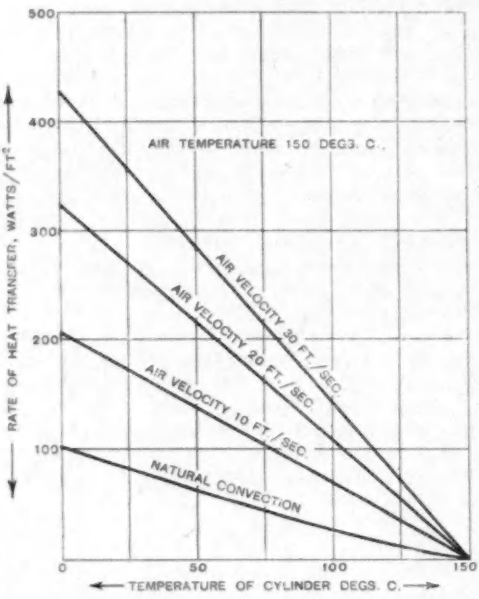

Fig. 2.—Variation of rate of heat transfer to a 10 inch diameter cylinder with cylinder temperature for different velocities of air at right angles to the axis of the cylinder.

The curves in fig. 1 (which have been calculated from this formula) give values of the rate of heat transfer for various oven temperatures between 100 degs. C. and 250 degs. C. and show how the rate of transfer decreases as the temperature of the body increases.

In practice, the heating effect taking place in a "convection" oven may be due in part to radiation from the oven walls. The nature of the effect of radiation depends on the design of the oven. Thus if the walls are at a temperature above the initial temperature of the article but lower than that of the air, the rate of heating will be greater initially and slower towards the end of the heating period if the article is exposed to the walls than if the transfer is due entirely to convection. Further, the final steady temperature will be lower than the air temperature by an amount sufficient to make the rate of heat transfer to the article by convection balance the rate of heat loss from the article to the walls by radiation.

Rates of heat transfer are increased considerably when the transfer is by forced rather than by natural convection. As in the case of natural convection, the theoretical treatment of the subject is involved, but to give some idea of the rates of heat transfer obtainable, curves have been plotted in fig. 2 for a cylinder 10 ins. in diameter with its axis perpendicular to the direction of air flow. It will be noted that rate of transfer at a given velocity is proportional to the difference between air temperature and cylinder temperature, and that it increases rather less than proportionally with increase in velocity.

IV. HEAT TRANSFER BY RADIATION.

1. General.

Radiation has long been used as a means of heat transfer for industrial work. Many types of high temperature electric furnace rely very largely on this method of heating, but it is only comparatively recently that it has been used to any great extent for relatively low temperature processes, requiring temperatures up to 300 degs. C.

The quantity of radiation which a body emits depends on the area and emissivity of its surface and on its temperature. The concept of the black body is of fundamental importance in considerations of heat transfer by radiation. A black body is defined as one which absorbs all the radiation incident upon it. It also has unit emissivity. Such a body at a temperature T degs. Absolute emits radiation at the rate :—

$$5{\cdot}7 \times 10^{-12}\ T^4 \text{ watts/sq.cm.}$$

In practice, a body not only emits radiation, but it also receives radiation from its surroundings. The net rate of heat transfer H from a black body at Absolute temperature T_1 degs. to black body surroundings at Absolute temperature T_2 degs. is given by the relation :—

$$H = 5{\cdot}7 \times 10^{-12}\ (T_1^4 - T_2^4) \text{ watts/sq.cm.}$$
$$= 5{\cdot}3 \times 10^{-9}\ (T_1^4 - T_2^4) \text{ watts/sq.ft.} \quad (3)$$

The quality as well as the quantity of the radiation varies with temperature, and the curves in fig. 3 give the spectral energy distribution from black body sources at temperatures varying from 600 degs. Abs. (327 degs. C.) to 2500 degs. Abs. (2227 degs. C.). Each curve refers to the same total rate of energy emission, so that the curves correspond to sources having surface areas inversely pro-

portional to the fourth powers of their surface temperatures. The table in the figure shows how surface area must be increased with decrease of temperature in order to keep the rate of emission at a constant level.

It will be noted from the curves that as the temperature of the source is increased, the proportion of short wave radiation also increases, and more of the radiation appears as visible light (*i.e.*, radiation in the region $0{\cdot}38\ \mu - 0{\cdot}78\ \mu$).

In practice, sources are rarely perfect black bodies, and the formulae for heat transfer are not so simple as those given above. In the case of a surface which is described as a "grey" body, the radiation is reduced proportionally at all wavelengths to values obtained by multiplying the black body intensities by a factor known as the emissivity E of the surface. The distribution curves have the same shape as the black body curves and the rate of emission of radiation is E times the rate for a black body. Sources having emissivities which vary with wavelength and temperature call for special treatment as laws for black and grey bodies are not applicable.

When radiation falls on a body, some may be reflected at the surface, some absorbed in the body, and some transmitted through it. It is only the proportion absorbed which produces a heating effect, and in general the absorptive power of a body varies with the wavelength of the incident radiation. It should be noted that with one or two special exceptions associated with the absorption of ultra-violet radiation (*e.g.*, photo-chemical effects and the excitation of fluorescence), absorption is accompanied by a heating effect irrespective of whether the radiation is in the ultra-violet, visible or infra-red region of the spectrum. It is not only infra-red radiation which causes heating.

Electrically heated sources of radiation may be designed to operate over a wide range of temperatures, and for convenience, they may be regarded as being of two main types :—

(*a*) those operating at temperatures so high that they must be enclosed in protective envelopes which are evacuated, or which contain an inert gas in order to prevent oxidation, and

(*b*) those operating at lower temperatures, where such protection is unnecessary.

The first type is represented by the lamp filament, an operating temperature of 2500 degs. Abs. (2227 degs. C.) affording a reasonable compromise between lamp life and rate of output of energy from a filament of given size. The second type comprises heating

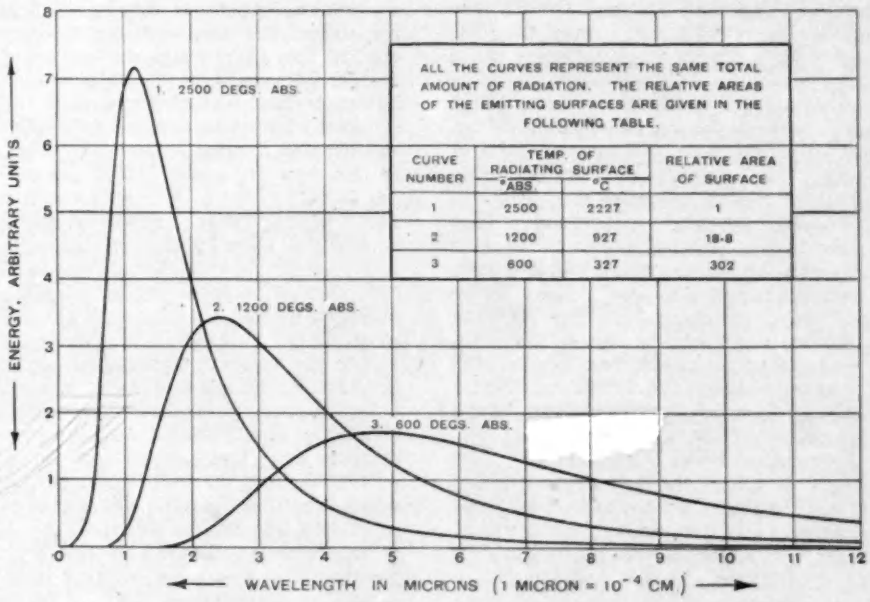
ALL THE CURVES REPRESENT THE SAME TOTAL AMOUNT OF RADIATION. THE RELATIVE AREAS OF THE EMITTING SURFACES ARE GIVEN IN THE FOLLOWING TABLE.
CURVE NUMBER
TEMP. OF RADIATING SURFACE °ABS.
TEMP. OF RADIATING SURFACE °C
RELATIVE AREA OF SURFACE
1 2500 2227 1
2 1200 927 18·8
3 600 327 302
1. 2500 DEGS. ABS.
2. 1200 DEGS. ABS.
3. 600 DEGS. ABS.
ENERGY, ARBITRARY UNITS
WAVELENGTH IN MICRONS (1 MICRON = 10⁻⁴ CM.)
0 1 2 3 4 5 6 7 8 9 10 11 12
1 2 3 4 5 6 7 8

Fig. 3.—Energy distribution of radiation from a black body at various temperatures.

elements of nickel-chromium and other heat resisting materials. In such elements, operating temperatures do not usually exceed about 1200 degs. Abs. (927 degs. C.), although higher temperatures are attainable if occasion demands. Curve 1 of fig. 2 shows the radiation distribution for a black body at 2500 degs. Absolute, and curves 2 and 3 show the distribution for the lower temperature sources.

2. Lamps as sources of Radiation.

One of the earliest references to the use of lamps on an industrial scale as sources of thermal radiation was a description of lamp equipment for stoving paint on motor car bodies.[2] Since then, lamp heating and paint drying have always been closely associated. The literature on the subject deals primarily with paint drying applications,[3, 4, 5, 6, 7] but some consideration has also been given to the theoretical aspects of the process.[8]

Reasons for choosing a lamp filament as a source of radiation are that it is compact and operates at a high temperature (thus having inherently low convection losses which are further reduced by the presence of the glass envelope) and that the direction of radiation from it may readily be controlled by means of reflectors. Such control is, indeed, essential, as radiation is emitted in all directions and must be re-directed to the body being heated. Moreover, the filament has an extremely low thermal capacity, with the result that the time taken in attaining working temperature is negligibly short.

The only type of lamp at present available for this purpose in this country has a tungsten filament in a gasfilled bulb and is rated at 115 volts, 250 watts. A low operating voltage was chosen because it permits a more robust filament construction. The lamps are usually connected in series on 200/250 volt supplies, which means that they sometimes operate above their rated voltage. It is possible to over-run the lamps a certain amount whilst at the same time maintaining a satisfactory life, as the filament temperature is relatively low. Fig. 4 shows the relation between operating voltage and rate of energy consumption.

In America, a wider range of lamps is available, including some types with internal reflectors. The American lamps have loadings up to 1000 watts, but, in general, flux densities of radiation are no higher than are used in this country, as reflector design (which has a bearing on flux density) has proceeded along rather different lines in the two countries.

The choice of reflector material demands careful consideration. The requirements of a good reflector are that it shall have a high reflectivity in the region of the spectrum over which radiation is emitted, that it shall not tarnish at its operating temperature, and that it shall withstand cleaning. Silver, gold, copper, rhodium and bright anodised aluminium all comply with the first condition but copper and silver must be considered unsuitable on account of their susceptibility to

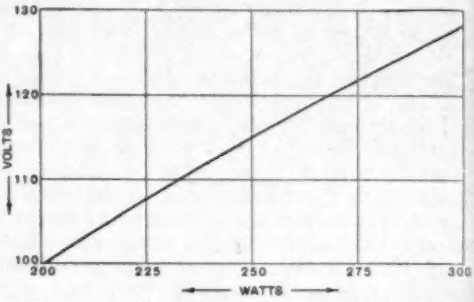

Fig. 4.—Voltage-loading relation, 115 volt 250 watt Osram infra-red industrial lamp.

tarnishing, whilst anodised aluminium is not at present available owing to supply restrictions. The two remaining metals, gold and rhodium, are both used on commercial equipment. Of the two, gold has the higher reflectivity, the difference being between 5 and 10 per cent at the wavelengths emitted by a source at 2500 degs. Absolute. However, as only half the radiation from the filament strikes the reflector, the net loss of energy resulting from the use of rhodium instead of gold amounts to less than 5 per cent. The principal compensating advantage of rhodium is that it is a much harder metal and is therefore more resistant to abrasion during cleaning.

In considering reflector design, one of two courses may be followed. The reflector may be regarded as associated with the individual lamp, in which case it will have a circular mouth and will be paraboloidal or ellipsoidal in shape or will follow some other contour designed to give the desired measure of uniformity or concentration on the object being heated. American designs and some designs in this country have followed this practice, which is indeed the most efficient when a very small area has to be irradiated. Applications of this type are limited in number and in practice, it is necessary in most cases to irradiate a considerable area. The second course, which is to regard a group of lamps

rather than a single lamp as the unit, may then be followed, and a trough reflector (fig. 5) may be designed for use in association with the group.

The trough method of construction offers several advantages over the individual reflector. Table 1 shows, for example, that higher intensities may be obtained as a result of the closer lamp spacing which the trough construction permits. 8 inches is about the minimum diameter which may be used in practice for the individual reflector.

When an area is to be irradiated uniformly, the trough reflector is more satisfactory than the individual type, as the latter tends to give a field of semi-overlapping circular patches which give rise to differences in intensity, depending on whether the point of the field under consideration happens to be opposite a lamp, a part of a reflector, or a space between reflectors. The effect is particularly noticeable when lamps with clear bulbs are used, as images of the filament show up as high intensity rings. It can be reduced somewhat by the use of pearl bulbs, and if the object being heated is moved about during heating, the consequences are less serious. Lack of uniformity shows up more on objects which are relatively poor thermal conductors than on thick sheets of good conductors, such as metals, as conduction through the latter assists in smoothing out temperature variations. A suitably designed trough reflector is free from these disadvantages, and the curves in fig. 6 show the distribution of radiation with a single trough reflector and with a bank of such reflectors touching one another. It is customary to include supplementary external reflectors at the ends of a bank in order to counteract

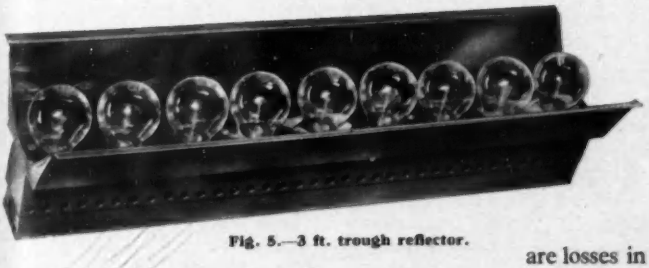

Fig. 5.—3 ft. trough reflector.

the falling off in intensity which would otherwise take place there.

Further advantages of the trough construction arise from the fact that gaps between adjacent reflectors may readily be avoided. Thus, in a plant consisting of two opposing banks, it frequently happens that a proportion of the radiation from the lamps and reflectors

TABLE 1.

Maximum intensities obtainable using 250 watt lamps in flat banks of individual and trough type reflectors.

	Individual reflectors nested together			Trough reflector with lamps at 4 inch centres along axis. Distance between centres of troughs : 10¾ inches
	Reflector diameter			
	8ins.	9ins.	10ins.	
Mean flux density (expressed in terms of electrical input)	650 Watts/ sq. ft.	513 Watts/ sq. ft.	415 Watts/ sq. ft.	837 Watts/ sq. ft.

is not at first intercepted by the articles, but passes through spaces between them and is re-reflected by the second bank before being absorbed. It will be apparent that this reflector bank should present a continuous reflecting surface, and gaps between nested individual reflectors do, in fact, represent a real loss, as they form 10 per cent of the total reflector area. Moreover, the light escaping through these gaps may be objectionable if other work is going on near the plant.

3. Comparison of Radiation and Convection as Methods of Heat Transfer.

The figures in Table 1 and the curves in fig. 1 may be used to show why it is that lamp heating gives more rapid rates of heat transfer than are obtained in the convection ovens operating at 100—200 degs. C. which it frequently replaces.

The maximum electrical input to a lamp plant built up of a single flat bank of trough reflectors is at the rate of 837 watts/sq. ft. The rate at which radiation is absorbed by an object is less than this figure, as there are losses in the lamps due to convection and to conduction along the filament supports, losses in the reflectors, and finally losses occurring because the object itself does not absorb all the radiation incident upon it (*i.e.*, because its absorptive power is less than unity). However, even in a case in which the total of these losses amounts to over 50 per cent, the net rate of absorption of radiation is still 400 watts/sq. ft.

It will be seen from fig. 1 that the corresponding initial rates of heat transfer to an object at 20 degs. C. in convection ovens at temperatures of 100 degs. C., 150 degs. C., 200 degs. C. and 250 degs. C. are only 47, 86, 129 and 176 watts/sq.ft. respectively.

With convection heating, the rate of transfer falls off rapidly as the temperature of the object approaches oven air temperature. In the case of heating by radiation, as the temperature of the object rises, its rate of absorption of radiation remains virtually unchanged, but its rate of heating decreases because it loses more heat by convection at the higher temperatures.

The effect is best seen by taking a concrete example and comparing the net rates of heat transfer at various temperatures to a flat panel in a convection oven at 150 degs. C. and to the same panel when irradiated between parallel banks of lamps and reflectors. The results of this comparison are set out in Table 2, where it has been assumed that air temperature in the lamp equipment is 20 degs. C. and that heat losses from the panel are by convection to air at this temperature.

In practice, the air inside a lamp heating plant is usually well above the figure of 20 degs. C. which has been assumed in Table 2. The effect of higher air temperatures is to increase the net rate of energy absorption, for whilst the rate of absorption of radiation remains at the same level, convection transfer at first supplements it and at later stages gives rise to a lower rate of loss than if the air temperature had been only 20 degs. C.

The experimental heating curves in fig. 7 illustrate very clearly the difference between the heating effects obtained in lamp plants and convection ovens. They give a rather favourable representation of convection oven conditions as the particular oven used for the experiment was well lagged, and air temperature recovered remarkably quickly after the panel was placed inside.

The main advantage of radiant heating is undoubtedly the reduction in heating time which it permits and this, of course, leads to a consequent reduction in the floor space occupied by the heating equipment. The ease with which the method may be associated with conveyors in flow production schemes is fre-

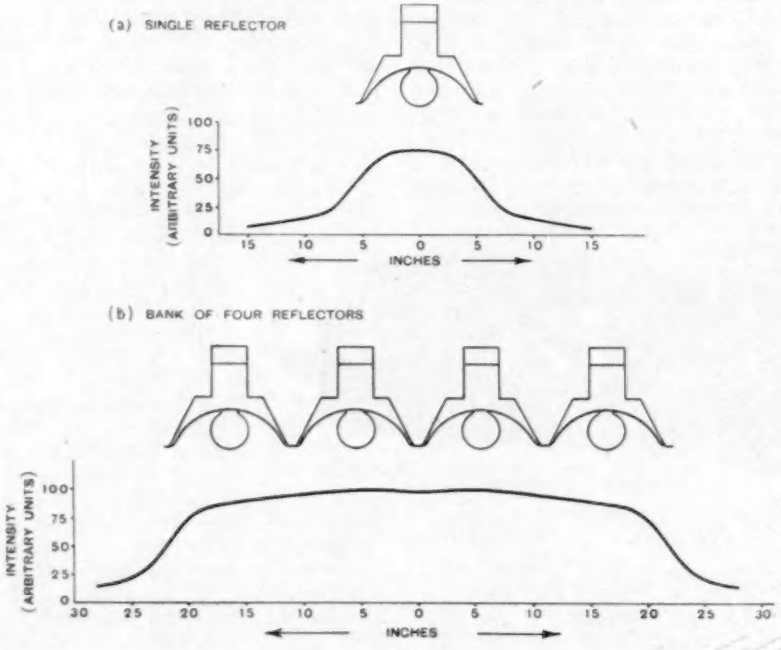

Fig. 6.—Intensity of radiation in a plane 9 ins. from the mouths of trough reflectors.

quently an important consideration and a further advantage arises from the fact that heating commences immediately a plant is switched on, so that there is no question of a long preheating period being necessary.

TABLE 2.

Comparison of rates of heat transfer at various temperatures to a thin metal panel heated from 20 degs. C. to 150 degs. C.

(a) In a convection oven at 150 degs. C.

(b) In a lamp plant consisting of a pair of parallel banks of trough reflectors having 250 watt lamps at 4 inch centres.

In the case of the lamp plant, it has been assumed that 48 per cent of the electrical energy supplied to the lamps is absorbed as heat by the panel, and that air temperature is 20 degs. C.

Temperature of panel Degs. C.	Net rate of energy absorption by each side of panel. Watts/sq.ft.	
	Convection Oven Air Temp. 150°C.	Lamp Plant Air Temp. 20°C.
20	86	400
40	70	391
60	54	381
80	40	367
100	26	353
120	13.5	337
140	3.5	322

4. Applications of Lamp Heating.

Before dealing in detail with the applications of lamp heating, it is appropriate to note that in many industrial processes, temperatures are referred to very loosely. Thus a process may be said to require one hour at 150 degs. C. when what, in fact, happens is that articles are placed in a convection oven the door thermometer of which is reading 150 degs. C. and are left in the oven for an hour. Even if the thermometer gives a true indication of initial oven air temperature, the temperature usually falls when the door is opened and the charge inserted, and it may take some time for it to recover. The articles are heated by convection, and may or may not reach a temperature of 150 degs. C. before the end of the hour, depending on the rate of recovery of air temperature and the relation between the surface area of the articles and their heat capacity. If the articles are metal and of heavy section, they almost certainly will not reach 150 degs. C. in the time mentioned.

The only satisfactory method of knowing what is taking place is to measure the temperature of the articles themselves by some such means as recording the e.m.f.'s of thermocouples attached to them. This is the practice usually followed in work on radiant heating, and is indeed the only possible method, as the indications given by mercury thermometers placed inside lamp heating equipment have little significance. By appreciating the usual meaning of "1 hour at 150 degs. C." it is easier to see why the same process may be carried out in a few minutes when lamp heating is used.

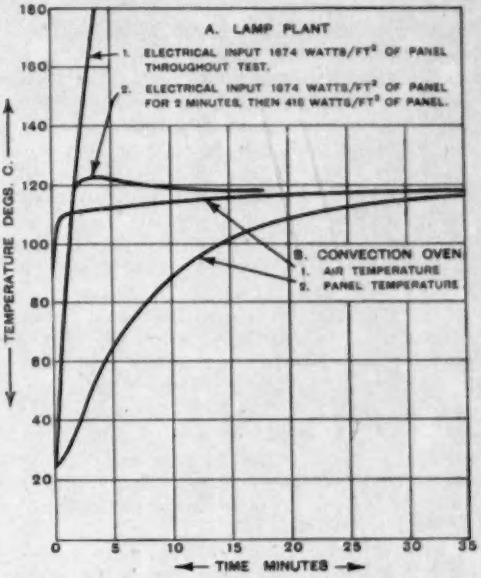

Fig. 7.—Experimental heating curves for a steel panel 0.120 ins. thick in a lamp plant and in a convection oven.

It is well to note also that very misleading results may be obtained from small scale experiments with lamp equipment unless the limitations of the apparatus are fully understood. The heating produced by a single lamp and reflector, for example, bears little relation to what takes place in a full scale plant, because the fields covered by the individual reflectors in a large plant overlap one another (thus producing higher intensities), and because convection losses are lower in a large plant.

Plant designs are prepared from a knowledge of the distribution of radiation from the reflectors of which the plant is composed together with accumulated experience of similar work, and the normal procedure is to carry out tests using the proposed reflector arrangement before finalising any design.

Paint Drying.

The stoving of paint on metal surfaces is without doubt the most widely used application of lamp heating. Reference has already been made to published work on the subject and it is not proposed in this article to deal in any detail either with the compositions of the various types of paint or with the chemistry of the stoving process. Further information on these subjects may be obtained from one of the standard text books such as that by Heaton.[9]

Paints may be divided broadly into two main types—those in which the drying process is a reversible one, and those in which it is irreversible. In the case of the first type (of which spirit varnishes and cellulose derivatives are examples) drying is due to evaporation of solvent, and the resultant film may be re-dissolved by re-application of the original solvent. These materials all dry relatively quickly without any heating, and the question of using lamp heating for accelerating the rate of drying seldom arises.

Drying of the second type is due to chemical reactions which take place during the drying process. The nature of these reactions depends upon the type of medium used in the paint. Thus the main reaction may be oxidation, due to combination with oxygen in the air, or it may be polymerisation—a reaction in the medium itself resulting in the formation of very large molecules from a larger number of relatively small molecules.

Paints of the irreversible type may be formulated primarily for air drying or primarily for stoving, but lamp heating may be used for accelerating the rates of drying of practically all of them. The reduction in drying time is greater for some types than for others, depending on the relation between temperature and rate of hardening and on the maximum temperature to which the film may be heated. The urea-formaldehyde and melamine-formaldehyde materials (both polymerising types) are particularly suitable for stoving with lamp equipment.

Drying times in lamp plants now used in production for stoving paint on a wide variety of articles fabricated from sheet metal vary from 45 secs. up to about 10 mins. according to the nature of the paint, the gauge and shape of the articles and the intensity of heating. Five minutes is a reasonable average time for this type of work and compares with times of 30—60 minutes in convection ovens operating at air temperatures between 100 degs. C. and 200 degs. C. Final temperatures with lamp heating tend to be rather higher than the general average of convection oven temperatures.

Fig. 8.—A 42ft. lamp plant for stoving paint on petrol cans. Loading: 252 kW.

The majority of lamp plants for drying paint are associated with conveyors, and stoving times are controlled by conveyor speed and plant length. In practice, the conveyor speed is adjusted to correspond with the rate of production, and the plant is switched in sections so that the length in circuit is such as to give the required stoving time at the particular conveyor speed being used. Typical installations having conveyors associated with them are illustrated in figs. 8 and 9. Limits are sometimes imposed on the temperatures to which articles may be heated for reasons such as the presence of soft soldered joints. In such circumstances, the intensity of heating is reduced during the later stages of stoving (for example by arranging to have the lamps spaced further apart). Advantages of combined lamp heating and conveyor equipment, in addition to those already noted, are that paint spraying may be done either manually or automatically on the conveyor line with a consequent saving in handling costs, and that the time elapsing between spraying and the end of stoving is so much shortened that much less dust deposition takes place on the wet paint film than in the longer convection stoving process.

The disposal of the volatile materials liberated during the stoving process does not present any difficulties. Natural convection currents are sufficient to ensure that they are carried upwards away from the work, and the usual practice is to place a cowl over the plant with just sufficient extraction to prevent them escaping round the sides rather than through the exhaust ductwork.

The design of lamp plants and the disposition of articles inside them must be such that excessive shadowing does not take place. For example, if an attempt were made to stove paint on three metal boxes abreast, the centre one would not heat to the same extent as the outer ones and the paint on it would not dry. When irregularly shaped metal articles are being stoved, it is virtually impossible to get a uniform intensity of radiation all over the surface, but fortunately conduction through the metal offsets this lack of uniformity and levels out temperature irregularities. Thus castings may usually be stoved without difficulty between flat banks of reflectors, and the rate of drying of paint on metal cylinders suspended in a line with axes vertical is the same on the parts of the surface opposite the lamps as on the parts facing neighbouring cylinders.

Whilst it is true to say that the applications most suited to lamp heating are those in which a single article is being produced in large quantities, the method is frequently suitable

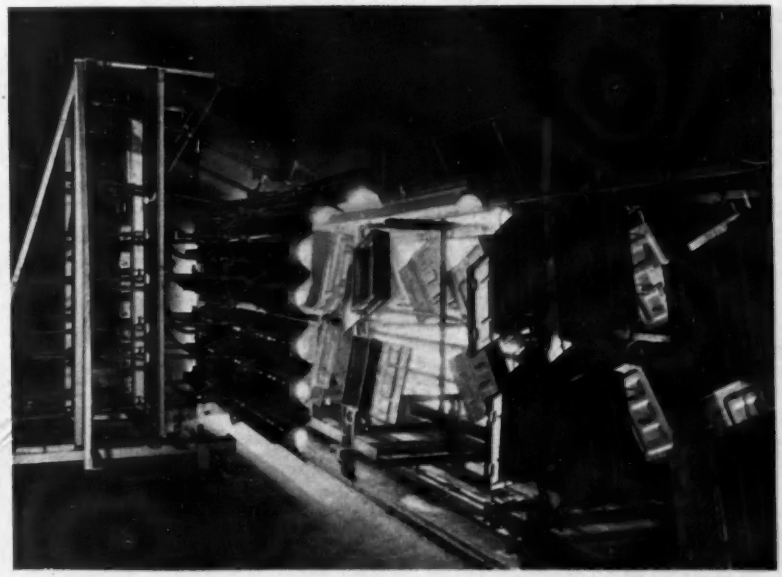

Fig. 9.—Fully adjustable 9ft. lamp plant for stoving paint on ammunition boxes. Loading: 94 kW.

also for mixed production. The extent to which it may be applied to the latter depends on the degree of similarity of the products and the stoving tolerance of the paint. As examples, it may be mentioned that all the components of binocular bodies and similar optical instruments are being stoved in 3 to 4 mins. in the same plant, and that all the components of a respirator are being stoved in a single plant in 45 secs. In other cases, a certain amount of special treatment may be necessary. Thus it is found that a wide range of radio panels and cabinets painted in either of two colours may be stoved in 4 mins. in the same plant, provided the panels are arranged two abreast so that they do not heat too rapidly through being irradiated on both sides. Again, the complete range of components of an aero engine, with the exception of the massive crankcase, may be divided into two classes requiring either 5 mins. or 10 mins. stoving in a plant consisting of a pair of flat reflector banks. The fact that heavy articles which heat comparatively slowly have also a slow rate of cooling helps in making possible the simultaneous stoving of assorted batches, as a certain amount of useful stoving takes place during the cooling period.

In all the applications so far considered, temperatures at the end of stoving have been 100—150 degs. C. or more. Lamp heating is often suitable also when much lower temperature limits are imposed. An interesting example is the drying of paint on finished airframe components such as fuselages, wings and tail planes which may not be heated to such high temperatures owing to the harmful effect they would have on internal electrical equipment, grease in bearings, etc. Plants for handling these components are not as a rule associated with conveyors and the usual procedure is to use a moderately high intensity until such time as the maximum allowable temperature is reached, and then to hold the temperature at this figure by automatically reducing the intensity. The curves in fig. 10 illustrate the heating effect obtained.

Lamp heating may be used for stoving paint or varnish on cardboard, wood, laminated plastic materials, asbestos cement, etc. as well as on metals. The problems encountered are rather different on account of the lower thermal conductivities of these materials as compared with metals. Thus, if painted cardboard cylinders are arranged in the same way as the metal cylinders considered earlier, the paint will not dry so rapidly on the parts facing neighbouring cylinders as on the parts facing the lamps, and the cylinders must be rotated in order to make them dry uniformly. Again, if paint is to be dried on a flat wooden panel, the intensity must be much more uniform than would be necessary for a metal panel, as any patchiness will not be levelled out by conduction through the material. The effect on stoving time of increasing the panel thickness is less with

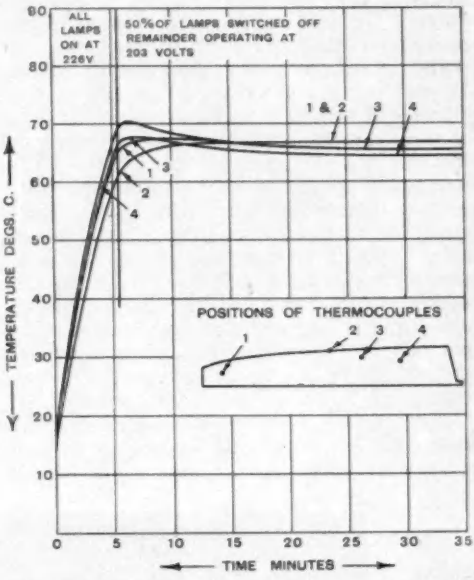

Fig. 10.—Curves showing how the temperature of an airframe component may be kept to a safe figure by reducing the intensity of heating after the initial pre-heating period.

wood than with metal, as it is possible with wood for an appreciable temperature gradient to exist between the surface and the centre.

In some of the earlier accounts of paint drying by radiant heat it was suggested that radiation had some effect in accelerating stoving other than its heating effect. It may readily be shown that this is not the case by painting a thin metal panel on both sides and exposing only one side to radiation, for it will be found that the paint films on the two sides are equally well stoved.

Paints differ in their absorptive powers for radiation, and attempts have been made to correlate colour and rate of heating. Care must be exercised in any such comparisons, as the colour of a paint is merely an indication of the region of the visible spectrum in which it happens to reflect, and no deductions can be drawn about its behaviour in the infra-red

part of the spectrum. Thus two paints may appear identical in colour but may yet differ considerably in infra-red absorptive power. Comparisons must take into account not only the pigment but also the other constituents of the paint, and the whole subject is one worthy of careful investigation.

Coil drying.

The drying of coil varnishes is a subject closely allied to paint drying. Transformer and choke coils are usually impregnated with insulating varnishes which must be baked in order that the chemical changes associated with hardening may take place. A temperature limit of about 150 degs. C. is set by the organic insulating material on the wire, and the stoving time in a convection oven is frequently as long as 24 hours. Much of this time is taken up by preheating as the coils have a high heat capacity, and lamp heating may be used to reduce it considerably. Times as short as are usual for paint drying are not possible, but total times of 2—3 hours for preheating and baking are frequently obtainable when some of the modern synthetic varnishes are used.

Drying foundry moulds.

Sand moulds must be dried before pouring in order to prevent the formation of blowholes due to the generation of steam by contact of the molten metal with damp sand. In many cases it is unnecessary to dry the whole of the mould; it is sufficient to dry the surface skin to a depth of 1 inch or less. This is often done by means of a gas torch, but the method is not altogether satisfactory because success is dependent upon the skill and experience of the operator and there is no means of checking that the work has been done effectively without spoiling the mould. With inexperienced operators, the percentage of reject castings is high, and automatic drying equipment is therefore attractive.

Lamp heating may be used successfully for certain types of mould, but it will be apparent that if drying is to be reasonably uniform, the surface of the mould must be free from deep cavities which are in shadow. The relation between temperatures at exposed parts of the surface of a mould and parts in shadow is illustrated by the heating curves in fig. 11. Lamp heating would not have been suitable for the particular mould used in the experiment as the sides and bottom of the vertical cavities would not have dried. For shallow moulds, however, it is very suitable and lends itself well to association with mechanised foundry methods.

In one mechanised foundry, more than thirty plants are installed over conveyors and are drying several different types of mould satisfactorily to a depth of $\frac{1}{16}$ inch in times of about 5 mins. In other cases, drying times may be as long as 30—45 mins., depending on the type of sand and its moisture content, on the depth of drying required and on the shape of the mould.

Accelerating the setting of adhesives.

The gluing of plywood to skeleton wooden rib structures is an important operation in the manufacture of wooden airframes. Synthetic glues, usually of the urea-formaldehyde type, have replaced the natural glues for this purpose on account of their greater moisture resistance and their immunity from fungoid growth. The synthetic glues have two constituents: the resin component or syrup, and an accelerator or hardener which

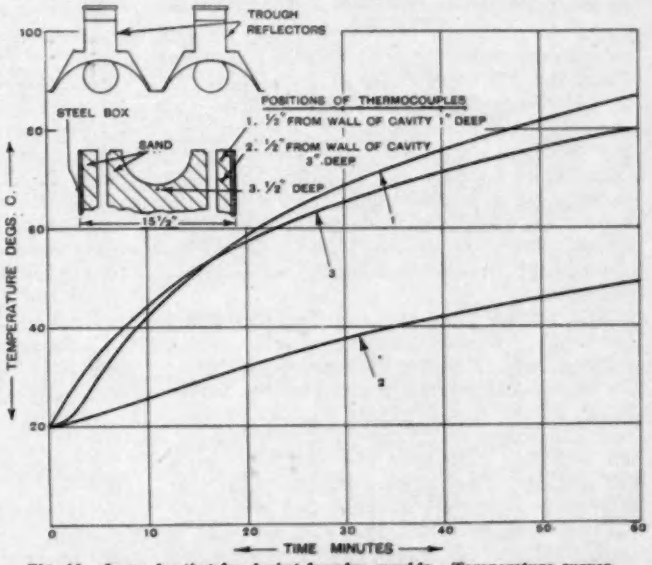

Fig. 11.—Lamp heating for drying foundry moulds. Temperature curves showing that the method is suitable provided the moulds are free from deep cavities.

enables setting to take place. These may be mixed immediately before use, or, alternatively, the syrup and hardener may be applied separately to the two surfaces to be joined together. Once the joint has been made, it must be maintained under pressure until such time as the adhesive sets, and this is seldom less than 5—6 hours at temperatures of 10—15 degs. C. Thus at normal factory temperatures, components must be allowed to remain on their supporting jigs for a considerable time, several jigs must be used and much floor space must be allocated to the glue-setting operation.

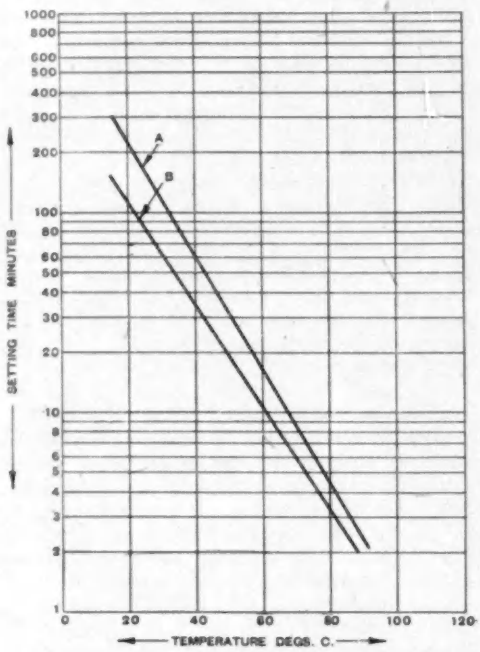

Fig. 12.—Relation between setting time and temperature for two typical synthetic resin adhesives used in airframe construction.

When these glues are heated, their setting times are reduced very considerably. The relation between setting time and temperature for two such materials is given by the curves in fig. 12 and it will be seen that at temperatures in excess of 70 degs. C., setting times are well below 10 mins. Wood has a poor thermal conductivity and if the glue joint is at any great depth (say more than 1 inch) conduction heating is a slow process and, if setting is to be accelerated, the capacity current method described later must be used. For thicknesses less than this, conduction becomes practicable and there are several ways in which it may be applied. In one—the autoclave method[10]—the component (built up, for example, of layers of plywood glued together and supported on a jig) is placed in a rubber bag which is evacuated and placed in a heat insulated tunnel fitted with heavy pressure-tight doors. Compressed air and steam are admitted to the tunnel and serve the double purpose of maintaining the necessary pressure on the glue joint and supplying heat to the surface of the plywood. The method gives greatly reduced setting times, but the rubber bag imposes a limit on the temperatures which may be used and acts as additional thermal resistance between the source of heat and the glue joint. Moreover, the apparatus, though very useful, is undoubtedly bulky and not too easy to handle.

There are other instances where pressure may conveniently be applied by means of steel strips tensioned over the surface, and it is sometimes possible to heat these strips by passing current through them, the glue joint being heated in turn by conduction from the strips. When this can be done it is a very effective method of heating as the efficiency is almost 100 per cent. In some cases, however, there are difficulties in getting sufficiently uniform heating owing to variations in the sizes of the strips, and it is not always easy to apply the method in production as a number of electrical connections must be made, and the strip tensioning devices must be insulated electrically from one another. For these reasons, strip heating finds its main application in the manufacture of relatively thin narrow spars, electrically heated strips being incorporated in the moulding jigs.

The difficulties of electrical connections and insulation in the larger assemblies may be overcome by irradiating the steel strips using lamps and reflectors. Whilst convection losses from the lamps and reflection losses make the overall efficiency rather lower than for the conduction method, the lamp method is very easy to apply and is less likely to necessitate alterations to existing jigs and tensioning devices.

The use of lamp heating for accelerating the setting of glue in a shaped component built up of two layers of ply with a balsa layer sandwiched between them is illustrated by the curves in fig. 13 which show the rates of heating at various positions in the assembly. In the experiment to which the curves refer, the intensity was limited to a figure at which wood temperature did not exceed 90 degs. C.

It will be seen that although there is very little temperature difference across the plywood, there is an appreciable difference between the two sides of the balsa on account of the greater thickness and lower thermal conductivity of the latter material. By reference to fig. 12, setting times may be estimated, and it can be shown that the joint nearer the surface would set in less than 15 mins. whilst that under the balsa would require 30—45 mins., depending on the rate of cooling after switching off the lamps.

In another method of construction, plywood skins are held in place and glue joints are maintained under pressure by using wooden strips tacked in position. These replace the tensioned steel strips, and similar accelerated setting may be achieved by irradiating the complete assembly.

Textiles.

Textile processes where some form of heating is required include the evaporation of moisture and the curing, or partial curing, of resin-impregnated cloths and cloths coated with synthetic rubbers and similar materials.

Lamp heating may be used successfully for drying a wide variety of types of cloth and lends itself well to use in continuous processes, the cloth being passed between banks of lamps until brought to the desired moisture content. Except for very heavy materials, or materials having a thick pile, the quality of the drying is very uniform. With these special materials, there is a tendency at rapid rates of heating for the surface to become drier than the centre, as water is evaporated more rapidly from the surface than it can diffuse through from inside.

The efficiency of the drying process depends to a great extent on the type of material being used and on the method of handling. Thin white silk, for example, has a fairly high reflection factor and also transmits some of the incident radiation. Since the heating effect is dependent only on the amount of radiation which is absorbed, reflection and transmission represent losses, and when this type of material is treated in a single thickness, the efficiency is relatively low. It may be increased considerably by arranging to have two or more thicknesses between the lamp banks (*e.g.*, by taking the material up and down over rollers set at the top and bottom of the plant). Radiation transmitted through one thickness is then absorbed by the others. The efficiency of drying varies from about 15 per cent for a single layer of thin white silk to 50 per cent or more for heavier dark coloured cloths.

The resin-impregnated materials which may be cured or partially cured include proofed and crease-resisting fabrics and impregnated materials used in the manufacture of laminated plastic boards.

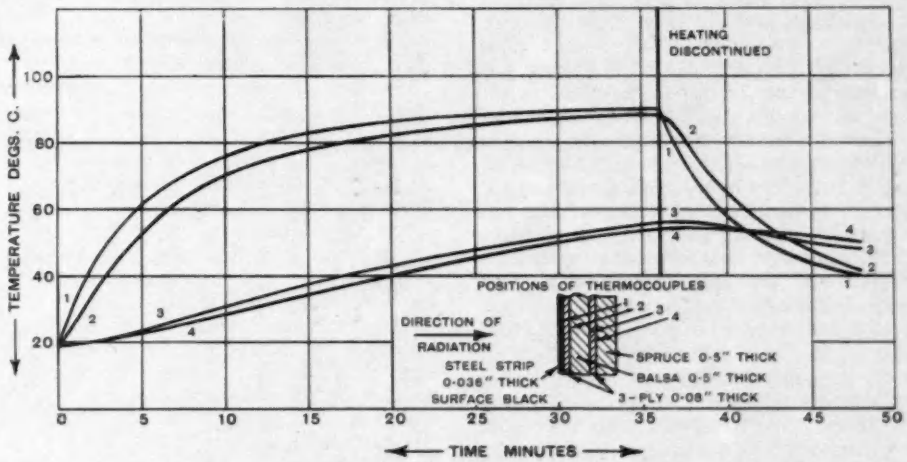

Fig. 13.—Lamp heating for accelerating the setting of adhesives. Heating curves showing temperatures in glue lines in a wood assembly tensioned by a steel strip and irradiated, using 250 watt lamps at 12 inch centres in trough reflectors.

Softening plastics.

Lamp heating is being used commercially for softening "Perspex" and cellulose acetate

sheet prior to moulding them on wooden formers into articles such as transparent windows for aircraft components. Softening times vary with thickness of material and intensity of heating. Thus $\frac{1}{16}$ inch thick sheet heated from both sides may be raised to moulding temperature in about 1 min., whilst $\frac{3}{8}$ inch thick sheet heated from one side only requires 10—15 mins.

Other applications include softening polyvinyl chloride strip for use in cable manufacture and softening laminated phenolic sheet preparatory to punching out radio components such as valve holders and terminal strips from it.

Miscellaneous applications.

The processes which have been referred to above are some of the more frequently encountered applications of lamp heating, but the list is by no means a comprehensive one. There are many other heating and drying operations where the lamp method may advantageously be employed. For example, printing inks may be dried, metal objects may be expanded in order that other parts may be fitted into them, moisture may be evaporated from coatings of vitreous enamel slurry, from thermoplastic moulding powders and from many other materials. An interesting application is the drying of gum on envelope flaps ; a single 3ft. trough will handle an output of over 17,000 envelopes per hour.

However, it must not be thought that lamp heating is suitable for all heating and drying processes. It would be quite unsuitable for heating metal surfaces having a high reflectivity. Neither would it offer any advantage for a process necessarily requiring a low temperature for a long time, or for one requiring uniform heating of a poor thermal conductor. In fact, it is necessary in all cases to consider the characteristics of the process as well as those of the methods of heating before deciding on the most suitable method for any particular case.

5. Sources of Radiation operating at Temperatures lower than that of the Lamp Filament.

The use of lamp heating for stoving paints led to the development of special finishes capable of producing very hard and corrosion resistant films on thin sheet metal in times as short as 1—2 mins. Mention has already been made of the fact that these short times are the result of rapid heating, and at an early stage during the development of lamp heating, it was apparent that whilst the intensities in use would enable convection oven times for articles of heavier section to be reduced very considerably, it would not be possible to stove these finishes on them in times as short as 1—2 mins. To obtain such times, higher intensities are necessary. Lamp heating intensities now in use are the maximum obtainable under present day conditions, and it is doubtful whether any very considerable increase may be expected even when more favourable conditions make possible a wider choice of lamps. Attention was therefore directed to lower temperature sources capable of giving greater rates of energy output.

The use of a lower operating temperature (usually 1200 degs. Abs. or less) necessitates certain changes in the source. In the first place, as the temperature is lower than that of the lamp filament, the radiating area must be increased (Eqtn. 3) to maintain the same rate of energy output. Secondly, there must be a further increase in area to give the desired increase in output. Thirdly, as the lower source temperature results in the emission of longer wavelength radiation (fig. 3) to which glass is not transparent, it is no longer possible to enclose the source in a glass envelope.

There are various types of source which take account of these differences. Nickel-chromium resistance wire, for example, operating at temperatures up to 900—950 degs. C. (or higher if circumstances make it necessary) is suitable and may conveniently be used in the form of coils supported in grooved porcelain formers. A source of this nature necessitates a rather different plant construction from that used with lamps. For example, it becomes preferable to reduce the losses from the back of the source by the use of lagging rather than by re-directing the radiation by reflectors, and it becomes necessary to take special steps to reduce convection from the exposed source, as this would otherwise represent a serious loss. Using equipment of this type, it is possible to work with intensities 5—10 times as great as are obtainable from lamps, and plants are in use commercially for stoving high temperature paints on steel articles having wall thicknesses of $\frac{1}{4}$ inch or more in times of 1—3 mins.

There are several interesting points of difference between sources of this type and sources of the lamp type. For example, the difference in plant construction (which tends to follow conventional furnace practice in the case of the lower temperature source) causes radiating surfaces of the low temperature type

to have a high thermal capacity, with the result that heating-up times are no longer negligible. Moreover, unless precautions are taken, source temperature may vary considerably according to whether or not objects are passing between the radiating walls. If a charge is passing through, the walls will reach equilibrium at a temperature at which the electrical input (less any convection losses and losses from the backs of the elements) is balanced by the output in the form of radiation to the charge. If, on the other hand, no charge is passing through, the walls will be unable to lose heat in this way and if the electrical input is maintained at a constant level, they will rise in temperature until such time as the increase in losses by convection and by conduction through the lagging is equal to the loss in the former case by radiation to the charge. Such changes in source temperature are clearly undesirable, as they give rise to differences in the rate of heat transfer depending on whether or not there are gaps in the flow of articles through the equipment, and, in practice, it is usual to control the source temperature thermostatically.

With lamp equipment, there is no appreciable change in source temperature due to the cessation of flow of articles through the plant. The chief reason for this is that the filament sources are so small in area compared with the reflectors that when there is no charge between the reflector banks the greater part of the radiation from one bank to the other falls on the reflectors rather than on the filaments, with the result that it is reflector temperature rather than filament temperature which increases. The amount of energy re-radiated into the plant by the reflectors when flow is resumed is very small as they have an extremely low emissivity, particularly for long wavelength radiation. A subsidiary reason is that if the temperature of the filament is increased by radiation falling on it, its resistance increases, and as the operating voltage remains constant, there is an automatic reduction in power consumption which tends to reduce the temperature.

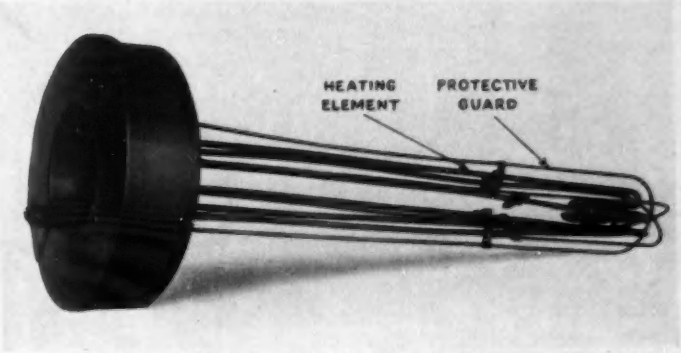

Fig. 14.—Low temperature sheathed wire type radiant heating element for internal heating of heavy cylindrical articles. Sheath temperature: 700—750 degs. C. Loading: 6 kW.

Other things being equal, there are two important advantages in keeping source temperature as high as possible. Firstly, it will be apparent that convection losses must be kept to a minimum, and equations (2) and (3) show that the ratio $\frac{\text{radiation loss}}{\text{convection loss}}$ increases considerably as source temperature rises, since radiation loss involves a 4th power whilst convection loss involves only a 5/4 power of the temperature. Secondly, a high source temperature is desirable because the rate of heat transfer to an article is much less dependent on the temperature of the article when source temperature is high than when it is relatively low. For example, if two sources operating at temperatures of 1200 degs. Abs. and 600 degs. Abs. (927 degs. C. and 327 degs. C.) are considered, and if their areas are such that they each transfer energy at the rate of 100 watts to an article at 300 degs. Abs. (27 degs. C.), the rates of transfer to the article when its temperature is increased

to 500 degs. Abs. (227 degs. C.) will be 97·4 watts and 55·2 watts respectively.

When an article is to be heated by radiation, an external source is not always the most suitable type to use; it is sometimes more convenient to use a source which can be placed inside the article. When this is done, the efficiency is usually higher than with the external source, because practically all the heat lost from it (whether by radiation or convection) is transferred to the article. Fig. 14 shows a source of this type which was designed for heating large cylindrical articles of heavy section. It consists of heating elements of the "sheathed wire" type in which nickel chromium resistance coils are embedded in refractory cement in heat resisting tubes, which constitute the radiating surface, operating at a temperature of 700—750 degs. C.

V. INDUCTION HEATING.

1. Capacity Current Heating.

There are many industrial processes in which slabs of materials of poor thermal conductivity such as wood, bakelite, cotton fabric, etc., need to be heated uniformly. Conduction from heated platens is not usually a satisfactory way of dealing with them as the rate of temperature rise at the centre of a material heated in this manner is so low. Heating by the passage of direct electric current would be attractive on account of the uniformity it would permit were it not that the electrical resistances of the materials are so great that impracticably high voltages would be required.

A material of this type may, however, be heated if it is placed between a pair of metal plates connected to a source of high frequency power, and during the last few years this method of heating has been receiving an increasing amount of attention.[11, 12, 13, 14] A material placed between plates in this way becomes the dielectric of a condenser and losses take place in it. Various theories have been put forward to account for these losses.[15] For example, if there are free ions in the dielectric, the rapidly alternating electrostatic forces to which they are subjected will cause them to oscillate, and work must be done in overcoming the forces resisting oscillation. Again, if the molecules behave as electrical dipoles, they will tend to align themselves with the field. As this is constantly changing in direction, they will be in continuous motion and work must be done against the forces resisting the motion. In either case, energy will be drawn from the high frequency source and will manifest itself by raising the temperature of the dielectric. The power absorbed in producing heat in this way is known as the dielectric loss of the material, and its magnitude in terms of the physical constants of the dielectric and the characteristics of the supply may be calculated in the following way.

Consider a simple parallel plate condenser with no dielectric material between the plates (fig. 15(a)). The relation between voltage V across the plates and current I_c may be represented by the vector diagram fig. 15(b). Voltage and current are 90° out of phase and there is no power loss; the condenser is said to be a perfect one.

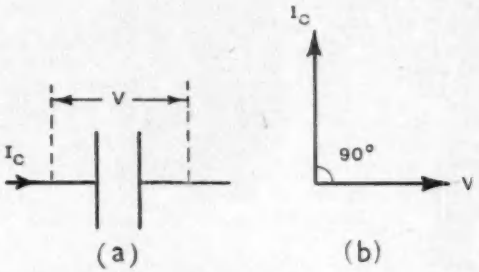

Fig. 15.—Condenser with no dielectric material between its plates. No loss of power takes place as voltage and current are 90° out of phase.

If now a dielectric is placed between the plates, the condenser ceases to be perfect as there is a certain loss in the dielectric which may be represented for the purpose of calculation as taking place in an equivalent shunt resistance S across the condenser plates (fig. 16(a)). S differs from an ordinary resistance in that its value varies with frequency. The current I_s flowing through S is in phase with the voltage applied to the condenser and the vector diagram for the imperfect condenser is given in fig. 16(b).

The power factor, cos θ, is given by

$$\cos\theta = \frac{I_s}{I}$$

Provided cos θ is small, we may write

$$\cos\theta = \frac{I_s}{I_c}$$

$$i.e.,\ I_s = I_c \cos\theta$$

The power loss P in the dielectric is given by the product $V I_s$.

Substituting for I_s, $P = V I_c \cos\theta$ watts (4)

But $I_c = V.2\pi f C$

where f = frequency of supply (cycles/sec.)
C = capacity of condenser (farads.)

and $C = \frac{KA}{4\pi d}$ electrostatic units

$= \frac{KA}{9\times10^{11}\times4\pi d}$ farads.

where K = dielectric constant
A = area of condenser plates (sq. cms.)
d = thickness of dielectric (cms.)

Therefore $I_c = \frac{KfAV}{18\times10^{11}d}$ amps.

and from eqtn. (4) $P = \frac{KfAV^2\cos\theta}{18\times10^{11}d}$ watts

$= 5{\cdot}55\times10^{-13}\frac{KfAV^2\cos\theta}{d}$ watts (5)

Assuming that all the power lost in the dielectric is used in raising the temperature of the material from T_1 degs. C. to T_2 degs. C. (*i.e.*, neglecting heat losses from the surface) the temperature rise $(T_2 - T_1)$ degs. C. and the power input P watts are connected by the equation :—

$$P = \frac{JAd\rho\sigma(T_2-T_1)}{t} \text{ watts} \quad \cdot \quad \cdot \quad (6)$$

where J = mechanical equivalent of heat = 4·18 Joules/cal.
ρ = density of material (gms./cc).
σ = specific heat (cals./gm. deg. C.)
t = heating time (secs.)

The power input P to produce any desired rate of heating in a material of known density and specific heat may be calculated from eqtn. (6).

The temperature rise may be expressed in terms of the electrical constants of the material and the voltage and frequency of the supply by combining eqtns. (5) and (6).

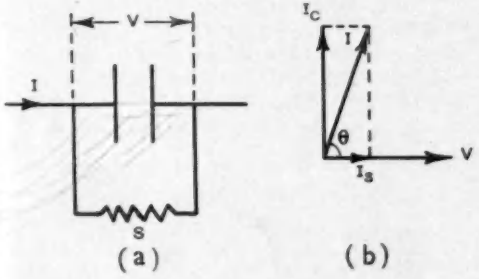

Fig. 16.—Condenser having a dielectric between its plates. The dielectric loss may be regarded as taking place in the equivalent shunt resistance S through which there is a current I_s in phase with the voltage V.

Thus from eqtn. (6) $T_2 - T_1 = \frac{Pt}{4{\cdot}18\,Ad\rho\sigma}$ °C

and substituting for P from eqtn. (5)

$$T_2 - T_1 = 1{\cdot}33\times10^{-13}\frac{fV^2tK\cos\theta}{d^2\rho\sigma} \text{ °C} \quad (7)$$

It will be seen from eqtn. (5) that the power loss in a material, when heated under standard voltage and frequency conditions, is proportional to the product of its dielectric constant K and its power factor $\cos\theta$. This quantity $K\cos\theta$ is known as the Loss Factor of the material. The loss factor is not as a rule a constant, for it is not altogether independent of frequency, and for some materials such as wood it may vary also with temperature and with moisture content. For the special case of a material with a constant loss factor it will be seen from eqtn. (7) that rate of heating increases in proportion to supply frequency and that at a given frequency it varies with the square of the voltage.

If there are any heat losses from the surface of a material heated by the high frequency method the temperature rise will be correspondingly lower than the value given by eqtn (7), but in general it is possible to make losses negligibly small by heating the condenser plates using ordinary resistance elements and by irradiating the exposed surfaces of the material (for example, by means of infra-red lamps and reflectors).

The equipment used for generating the high frequency power is very similar to a radio transmitter and a correspondingly wide range of output frequencies is available. For practical purposes, frequencies are usually within the range from 1 megacycle/sec. to 100 megacycles/sec. (300 metres to 3 metres) and frequencies of 10—20 Mc/s (30—15 metres) are suitable for a wide variety of applications. The lower frequency limit is fixed by the voltage which may be used without risk of breakdown, voltage varying inversely with the square root of the frequency for a given rate of heating. The upper frequency limit is sometimes set by considerations of valve design and sometimes by the dimensions of the material being treated. Thus, if a quarter of the length of a standing wave in the material at the working frequency approaches the length of the article, heating becomes non-uniform unless special precautions are taken.

An experimental set having an output of 2½ kW at a frequency of 10—15 megacycles/sec. is illustrated in fig. 19

Voltages used are high (of the order of kilovolts) and suitable safety precautions have

to be taken to safeguard operators. Steps have also to be taken to minimise radiation from the equipment as it would otherwise interfere with radio reception.

The efficiency of a high frequency set, expressed as the ratio $\frac{\text{input power to the load}}{\text{total input from mains}}$ is about 50 per cent. Thus a set rated as having an output of 4 kW will draw 8 kW from the mains supply.

The capital cost of high frequency heating apparatus is high compared with the cost of other forms of industrial heating equipment, and for this reason the process is usually to be recommended only for applications similar to those described below where other methods are unsuitable. Maintenance costs, which arise chiefly in connection with valve replacements, are not excessive, as the conditions of use are such as to ensure a long life for the valves.

2. Applications of Capacity Current Heating.

Production of laminated wood.

The processes which benefit most from capacity current heating are those in which materials which are good thermal insulators require heating uniformly and rapidly. In the manufacture of plywood, laminated aircraft spars, and laminated wooden blocks for airscrews, layers of wood are cemented together using adhesives, which are usually of the phenol-formaldehyde or urea-formaldehyde type. Some of these materials must be heated before they will set, and in the case of those which set at room temperature, mention has already been made of the way in which setting time may be reduced by heating (fig. 12).

The usual method of raising the temperature of a stack of veneers or laminations is to place it between heated platens in a press and to leave it for a sufficient time for heat to be conducted through to the centre. The variation with time of the temperature distribution in a material placed between constant temperature platens in this way depends on the thermal diffusivity of the material and may be calculated.[16, 17] The curves in fig. 17 show how the temperature in a 6 in. thick block of wood initially at 15 degs. C. varies with position and time when the block is placed between platens maintained at 150 degs. C. Woods do not vary greatly in thermal diffusivity, and in the curves, a value of $18{\cdot}9 \times 10^{-4}$ $cm^2/sec.$ has been assumed. This figure is approximately correct for spruce and for white pine.

The H.F. method of heating gives entirely different results from those of fig. 17. So long as precautions are taken to ensure that heat losses from the surface are kept to a low figure the rate of temperature rise is independent of position in the block. The curve in fig. 18 shows the temperature rise at the centre of a 6 in. stack of spruce boards heated by the H.F. method. The particular rate of heating used in this experiment is typical, but is by no means the maximum obtainable; a higher power input would have given a greater rate of heating. The sharp bend in the curve occurring at a temperature just above 100 degs. C. is due to the additional latent heat which has to be supplied when the moisture in the wood boils and escapes.

When wood is heated above 100 degs. C. at high pressures it is frequently necessary to allow it to cool before removing it from the press, as damage would otherwise be caused through high pressure steam forcing its way out. It must be remembered that whilst the H.F. method enables the wood to be heated very rapidly, it does not assist at all with cooling and the greatest overall time saving is obtained with adhesives which set at lower temperatures than 100 degs. C. and which do not need to be maintained under pressure during cooling.

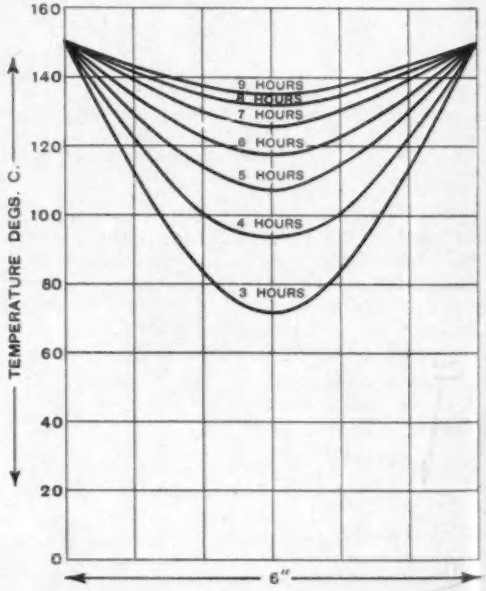

Fig. 17.—Variation with time of the temperature distribution in a 6 inch block of wood initially at 15 degs. C., when the surfaces of the block are placed in contact with platens maintained at 150 degs. C. Thermal diffusivity of wood taken as $18{\cdot}9 \times 10^{-4}$ $cm^2/sec.$

The power input per square foot of surface to heat a block 6 in. thick at the rate represented by the first part of the curve in fig. 18 may be calculated from eqtn. (6). If density and specific heat are taken as 0·41 gms./cc. and 0·35 cals./gm. deg. C. respectively, power

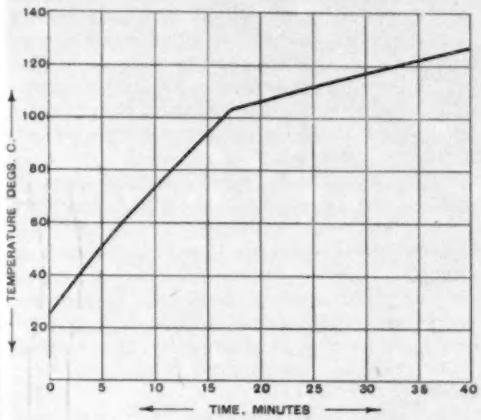

Fig. 18.—Temperature at centre of 6 inch block of spruce heated by the high frequency method.

input works out at 645 watts, and the quantity of energy required to heat 1 cu. ft. of the wood is 0·47 kWh per 100 degs. C. temperature rise. These figures refer to input to the wood, and not to power drawn from the mains; the latter would be approximately double the values given.

The voltage necessary to produce this rate of heating may be calculated from eqtn. (7). If the frequency of the supply is 15 megacycles per second and the loss factor of the wood is 0·08, substitution in this equation shows that 4000 volts must be applied across the plates in order to heat the 6 in. thick block at the specified rate.

Manufacture of laminated plastic materials.

The production of laminated materials from resin impregnated paper and fabric are other applications where chemical reactions associated with the curing of synthetic resins are accelerated by high frequency heating and the problems arising are generally similar to those encountered with laminated wood.

With these materials and also with laminated wood it is usually preferable to manufacture two similar stacks of material at a time rather than make them singly, as it is then possible to use both the upper and the lower press platens as earthed electrodes, the live electrode being placed between the two stacks. This arrangement makes it unnecessary to insulate platens from one another and simplifies press construction.

Drying rayon yarn.

An application of a rather different type is the drying of rayon yarn. In production, this material is wound on to spools, and before it is dried, it has a moisture content of about 100 per cent. The drying process in a convection oven is necessarily a slow one, taking about 10 days for completion. If an attempt is made to accelerate it by using higher air temperatures, the rate of evaporation from the surface of the rayon cake exceeds the rate at which moisture can percolate through from the inside. In consequence, the outer layers of the cake dry more rapidly than the inner ones and tend to contract more, thus suffering mechanical damage due to the tension under which they are placed.

With the high frequency method it has been found possible to boil the water away in 30 mins. or less without damaging the yarn.

Pre-heating plastic moulding materials.

Yet another application is the pre-heating of thermo-setting plastics prior to moulding.[11, 13] In ordinary compression moulding of thermo-setting materials, a measured amount of the uncured plastic (usually in the form of powder or pellets) is placed in one section of a heated mould and the other section is pressed down into contact with it. The moulding material is caused to flow to all parts of the mould and is cured by heat conducted to it. If the shape of the mould is at all complicated, high pressures must be used as the material in its initial state does not possess good flow properties. Mould design is, in fact, restricted by limitations imposed by the flow properties of moulding materials.

These materials have, however, an important property which enables this disadvantage to be overcome: they may be made to flow very readily at temperatures just below the curing temperature, provided they are heated rapidly. Rapid heating is essential as some curing takes place below the normal curing temperature, and this pre-curing must be avoided. The limitations of convective transfer for pre-heating are considerable, for whilst it is possible to heat the surface of the powder or pellets at a sufficiently rapid rate, it is not possible to heat the centre. In practice, oven temperatures are usually limited to about 100 degs. C., this being sufficiently low to avoid pre-curing on the surface, and the heating time is

made as long as possible to gain the maximum benefit from conduction to the centre. This treatment is an unsatisfactory compromise, as the improvement in flow properties is nowhere near as great as it would be at temperatures 20—30 degs. C. higher.

With high frequency heating, there is no difficulty in attaining these higher temperatures throughout the material in times of about 1 minute and full advantage may be taken of the reduced moulding pressures. The wear on moulds and on inserts is reduced, and heavier sections and more complicated shapes may be moulded. An additional advantage is that curing times may be reduced very considerably on account of the reduced initial temperature difference between the preheated material and the mould.

Joining thermoplastic materials together.

The processes so far considered have all involved heating thick sections of insulating materials. The joining together of thin sheets of thermoplastic material, and of sheets of fabric coated with thermoplastic material (as used in the manufacture of waterproof clothing) are applications where quite thin sections may advantageously be heated by the high frequency method.[14] Alternative methods for joining these materials are by sewing and by pressing between heated rollers. Sewing has the disadvantages of weakening the material and of requiring a subsequent treatment to render the seam moisture-proof, whilst the hot roller method tends to cause over-heating at the surface before the joint has reached a sufficiently high temperature for softening to take place. By using high frequency heating, with fairly massive rollers as electrodes, it is possible to heat the inside of the seam to the softening temperature, and at the same time keep the surface cool by conduction away through the rollers. Materials between 0·001in. and 0·005in. in thickness may readily be joined together, and relatively rapid rates of travel may be employed.

3. Eddy Current Heating.

When an alternating current flows through a coil it sets up an alternating magnet field, and if a metal article is placed in this field, alternating currents are induced in it. When these currents flow through the metal there is an energy loss due to the resistance which has to be overcome, and if the metal is magnetic there is an additional loss on account of the work done in causing the molecules to align themselves with the applied field. The two losses are known as eddy current and hysteresis losses respectively, and the electrical energy absorbed in the article is converted into heat. In the design of electrical machinery, it is frequently necessary to take special precautions to minimise losses of this nature. Transformer cores, for example, are built up of laminations which are insulated electrically from one another in order to reduce eddy currents. The losses may be turned to good account when it is desired to produce a heating effect, and the induction method of heating is being used to an increasing extent in many industrial processes.

Low frequency induction heating has been used for some years for melting metals and for heating them before forging. Currents are induced in the metal itself, or in a surrounding crucible made of an electrically conducting material, and heating is reasonably uniform throughout the charge. The chief use of induction heating at frequencies up to about 1000 cycles/sec. has been for purposes such as these.

Recent developments have been concerned more with the use of higher frequencies at which eddy currents are confined to the surface skin of the article being treated.[18,19,20,21]

It may be shown that when a cylinder is heated by eddy currents, over 90 per cent of the heat is generated in a peripheral layer whose thickness p cms. (which is assumed to be small compared with the radius of the cylinder) is given by the relation.

$$p = \frac{1}{2\pi}\sqrt{\frac{10^9 \rho}{\mu f}} \text{ cms.} \quad \cdot \cdot \quad (8)$$

where ρ = resistivity (ohm. cms.)
μ = permeability
f = frequency (cycles/sec.)

For carbon steel at room temperature, the thickness of the layer is about $\frac{2}{\sqrt{f}}$ cm. At temperatures above the Curie temperature (at which steel loses its ferro-magnetic properties) the permeability decreases to unity and there is an increase in the resistivity. The layer thickness then increases to $\frac{50}{\sqrt{f}}$ cm. Thus at a frequency of 1 megacycle/sec., the effective skin thicknesses are about 0·002 cm. and 0·05 cm. for steel at room temperature and at 800 degs. C. respectively.

A method of heating which produces a skin effect of this nature is ideally suited for use in surface hardening operations where it is

necessary to provide a hard skin on a portion of a steel article whilst at the same time allowing other parts to retain their original properties. The length of the article over which heating takes place may readily be adjusted by suitable choice of coil length, and local hardening may be carried out very simply by heating to the necessary temperature followed by quenching. The process is much easier and cheaper in application than the alternative of copper plating the portions which are not to be hardened and case-hardening the remainder by carburising. Moreover, it is much less likely to give rise to distortion, and frequently enables articles which could not be treated by alternative methods to be hardened satisfactorily.

It will be apparent that although high frequency eddy currents cause heat to be generated in the surface skin of an article, it will rapidly be conducted through to the core unless special precautions are taken. These precautions take the form of generating the heat at an extremely rapid rate so that the whole operation of heating and quenching is over before there is time for any appreciable amount of conduction to take place. Thus input powers for surface hardening are of the order 1000 watts/sq.cm. (*i.e.*, well over one thousand times the maximum intensity obtainable from lamp heating equipment) and heating times to a temperature of 800 degs. C. are of the order of seconds.

The power absorbed in a metal at constant heating coil current varies with the square root of the product of its resistivity and permeability. For steel over the range from room temperature to the Curie temperature, the resistivity increases gradually with temperature whilst the permeability decreases somewhat. The net effect is that the rate of energy absorption increases. At the Curie tempera-

Fig. 19.—Portable experimental high frequency heating set with protective casing removed. Output: 2½ kW at 10—15 megacycles per sec.

ture, the permeability suddenly falls to unity and there is a corresponding drop in the power absorption in the peripheral layer. This has the important effect of greatly diminishing the rate of temperature rise at the surface and makes surface overheating less likely to take place.

The sources of high frequency power which may be used for eddy current heating are of three types. The first is the rotating generator which, in practice, has an upper frequency limit of about 15,000 cycles/sec. The second is the valve oscillator. As a rule, this type is used when higher frequencies (normally of the order of 1,000,000 cycles/sec.) are required, but it may also be used at lower frequencies within the range covered by the rotating generator. The third type—the spark gap oscillator—is used less extensively than the others. It has a frequency range of about 50,000—300,000 cycles/sec.

The first type is suitable for surface hardening relatively large components as well as for melting and forging. Machines operating towards the upper frequency limit are suitable also for hardening smaller components provided they are of simple shape and do not require too low a depth of hardening. The higher frequency sources must be used if the articles to be heated are irregular in shape, or if a small depth of hardening is required. It is frequently necessary also to use high frequencies when heating metals which are good electrical conductors.

The coils used for eddy current heating at high frequencies are usually wound in a single layer and often consist of only a single turn. When it is necessary to heat an article more at one part of its surface than at another, the coil is so constructed that the turns are more closely spaced over the area where the greater intensity is required.

Articles whose surfaces may be hardened include crankshafts, sprockets, gear wheels, cams, brake drums and piston rings. It should be noted that internal surfaces of cylinders may be hardened by the use of an internal heating coil and that slotted pipe dies may be hardened inside and outside by the use of an external coil. The method is used extensively for heating the internal electrodes of thermionic valves during manufacture in order to expel the last traces of gas from them. Other applications include brazing, soldering and zonal tempering. An interesting use is for heating and flowing an electrolytically deposited coating of tin on steel plate.[22] The plate passes continuously through a coil, and the very high rate of heating, together with the ease with which heating may be discontinued in the event of a stoppage, make the method particularly attractive.

Accurate control of heating time is necessary in most of these applications and the whole process of inserting the charge in the coil, switching the current on and off, and quenching is very often carried out automatically in special machines.

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The Selection of Fans.

By B. B. DALY, B.Sc., A.M.I.H.V.E.

INTRODUCTION.

THE increasing use of forced air circulation devices as a means of heat transfer is perhaps the chief of several factors which have led to the recent introduction of fans into branches of engineering in which they were previously little known. Experience provides many examples in which the design of the airways and the selection of the type, size and speed of fan are far from conducive to efficient operation; this is probably because the designer made no contact with the subject during his engineering training, while the literature is more suited to the specialist than to the occasional user.

In this article a summary is given of the laws of fan operation together with typical performance data for the more common types. It is shown that, while the prediction of fan performance is straightforward, the converse problem of selecting a fan for a given performance is soluble only by trial and error or by cumbersome and little used "specific speed" and allied methods. A description is then given of a method for the ready solution of both performance prediction and fan selection problems, which has been in successful use in the writer's design office for a number of years.

THE FAN CHARACTERISTIC.

The performance of a particular fan is completely defined by curves such as those of fig. 1 for a 24 in. 920 r.p.m. propeller type fan. Furthermore, if the discharge area of the fan casing is known, it is sufficient to plot one of the quantities H_t (total fan head) or H_s (fan static pressure), since their difference H_v is the average velocity head at discharge, which can be calculated approximately from the air flow and area. This velocity head is proportional to the kinetic energy of the air (or gas) stream at that point. Throughout this article attention will be concentrated on H_s since this is the pressure directly available for overcoming resistance external to the fan; it must not, however, be forgotten that some part of H_v may be recovered by efficient external velocity transformation and used for the same purpose.

The assessment of resistance is outside the scope of this article, but one point is so often overlooked as to warrant mention. The characteristics are drawn for specific conditions of intake and discharge, usually intake from and discharge to either the ambient atmosphere or ducts of dimensions equal to the inlet and outlet. Suitable test conditions for the various types are defined in British Standard No. 848. If, however, obstacles exist which deflect or obstruct the airstream in the immediate neighbourhood of the inlet or outlet, the flow pattern through the impellor, and therefore the fan performance characteristic, may be substantially modified. If the presence of such an obstacle is unavoidable, the only safe method of predicting performance is to carry out a full-scale or model test.

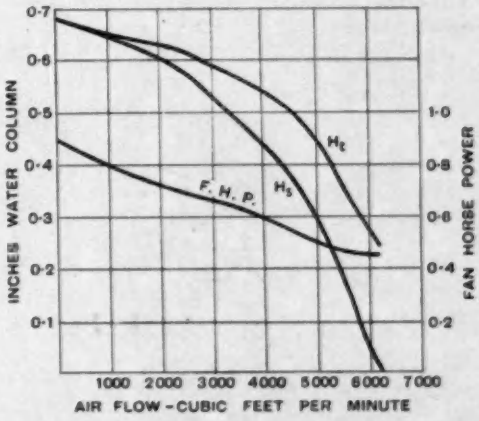

Fig. 1. Performance of a particular 24 in. propeller type fan running at 920 r.p.m. in standard air.

DEFINITIONS AND PRIMARY RELATIONS.

D = Impellor Diameter, feet.
N = Rotational Speed, r.p.m.
Q = Air Flow, cubic ft. per min.
H_t = Total Fan Head, ins. W.G.
H_s = Fan Static Pressure, ins. W.G.
H_v = Velocity Head at Discharge, ins. W.G.
V = Discharge Velocity, ft. per min.
ρ = Air or Gas Density, lbs. per cu. ft. = 0·0763 for air at 60 degs. F. and 30ins. Bar.
ρ_s = ρ /0·0763 (unity for standard air).
f.h.p. = Fan Input Horse Power.
a.h.p. (total) = Air Output H.P. based on H_t.
a.h.p. (static) = Air Output H.P. based on H_s.
η_t (total) = Fan efficiency based on H_t.
η_t (static) = Fan efficiency based on H_s.

The fan characteristic of fig. 1 may be generalised as shown in fig. 2 by the use of the dimensionless coefficients K_q, K_s, K_t and K_p defined by equations (1) to (4) below. The relationships of fig. 2 can then be applied to a family of fans geometrically similar to that of fig. 1, but differing in diameter and speed.

$$Q = K_q N D^3 \quad . \quad . \quad . \quad . \quad . \quad (1)$$
$$H_s = K_s \rho_s N^2 D^2 \quad . \quad . \quad . \quad . \quad (2)$$
$$H_t = K_t \rho_s N^2 D^2 \quad . \quad . \quad . \quad . \quad (3)$$
$$\text{f.h.p.} = K_p \rho_s N^3 D^5 \quad . \quad . \quad . \quad . \quad (4)$$

K_s and K_t do not appear to be dimensionless in the above equations, but this is only because of the conventional use of H "inches of water column" to represent a pressure. The characteristics are completely defined if any three of the coefficients K_q, K_s, K_t, K_p and η_t are known, since :

$$\text{a.h.p. (static)} = 0{\cdot}000158\, Q\, H_s \quad . \quad (5)$$
$$\eta_t \text{ (static)} = \text{a.h.p. (static)} \div \text{f.h.p.}$$
$$= 0{\cdot}000158 \frac{K_q K_s}{K_p} \quad . \quad (6)$$
$$V = \frac{C_v Q}{D^2} \quad . \quad . \quad . \quad (7)^*$$
$$H_v = \rho_s \left(\frac{V}{3997}\right)^2 \quad . \quad . \quad (8)$$
$$K_t - K_s = \frac{H_v}{\rho_s N^2 D^2} = \left(\frac{C_v K_q}{3997}\right)^2 \quad (9)$$

Strictly speaking, H_v is the average velocity head at discharge, not the head at average velocity. The distinction is usually ignored.

* C_v will be a constant for any particular family.

LIMITATIONS TO FORMULAE.

While the above simple relations may be used for the majority of applications with the coefficients, K_q, K_s, K_t, K_p taken as constant, they do not hold over an unlimited range of N and D. The following are the principle limitations :—

(*a*) The formulae ignore the compressibility of the gas used and only hold so long as the total fan head is negligible in comparison with the absolute gas pressure. The upper limit of applicability in standard air is about 25 inches water column, when the error in a.h.p. is some 2 per cent.

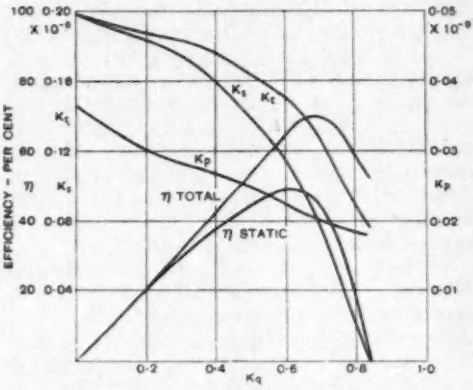

Fig. 2. Generalised characteristics for fans similar to that in fig. 1.

(*b*) The assumption of geometrical similarity does not usually hold for a wide range of D ; thus, large fans are usually more efficient than small ones owing to the reduced proportionate size of imperfections such as rivets, welds or surface roughness. This effect can be neglected in preliminary selection, and corrected by the use of the standard test data for the particular fan selected.

(*c*) The coefficients are, strictly speaking, functions of the Reynolds Number of the flow ($D V \rho/\mu$ where μ is the viscosity of the gas). In practical cases the flow will be fully turbulent, and the coefficients are usually assumed constant; if, however, doubt exists in predicting the performance of a large fan by means of tests on a small model, the tests should, if possible, be taken at the same value of D^2N.

(*d*) Apart from the Reynolds Number effect, the coefficients are independent of peripheral speed up to about 60 per cent of the velocity of sound, which is 65,000 feet per minute in standard air. As the velocity of sound is approached, however, the efficiency begins to fall rapidly, and this effect has been found a severe limitation in the design of superchargers for aero-engines.

THE PROBLEM OF SELECTION.

In the consideration which follows, attention will be concentrated on the air-flow Q and fan static pressure H_s which together define the duty, and the diameter D and speed N which together define the fan. Equations (1) and (2) together with curves such as fig. 2 provide all that is necessary to determine the performance of a fan belonging to the family in question.

When it is required to select a fan for a given duty, the position is not so simple. Manufacturers' catalogues provide voluminous performance data for their products, and these are adequate when dealing with conventional applications; the range of possible types, sizes and speeds is so wide, however, that new developments are very apt to call for duties outside the scope of the catalogues. In the following paragraphs an indication is given of the position of the user who wishes to make an analysis leading to preliminary selection of diameter, speed and type, before consulting those manufacturers in a position to meet his requirements.

Ordinarily, an arbitrary selection is first made of two of the three variables: diameter D, speed N, and type (fig. 2). Suppose the type and diameter have been fixed, then if the relationship between K_q and K_s could be put into a suitable mathematical form, equations (1) and (2) would determine the value of N, or alternatively would determine D if N were fixed. Such a form cannot, in general, be found without gross approximation, and in practice recourse is usually had to trial and error.

"SPECIFIC" METHODS.

Reference may be made here to certain methods which have been proposed for the solution of the selection problem without trial and error and with the minimum of arbitrary selection. Three dimensionless quantities are calculated from equations (10), (11) and (12), below, and from data such as fig. 2 (actually two quantities would suffice); these are plotted against efficiency, as shown in fig. 3. Similar equations can be built up on the total fan head H_t, while equation (13) is an alternative form of equation (12), which will be familiar to turbine engineers.

$$\text{Specific Tip-Speed} = D\,N\,H_s^{-\frac{1}{2}}\,\rho_s^{\frac{1}{2}} = K_s^{-\frac{1}{2}} \quad . \quad . \quad . \quad (10)$$

$$\text{Specific Diameter} = D\,Q^{-\frac{1}{2}}\,H_s^{\frac{1}{4}}\,\rho_s^{-\frac{1}{4}} = K_q^{-\frac{1}{2}}\,K_s^{\frac{1}{4}} \quad . \quad . \quad (11)$$

$$\text{Specific Speed (1)} = N\,Q^{\frac{1}{2}}\,H_s^{-\frac{3}{4}}\,\rho_s^{\frac{1}{2}} = K_q^{\frac{1}{2}}\,K_s^{-\frac{3}{4}} \quad . \quad . \quad (12)$$

$$\text{Specific Speed (2)} = N\,(\text{a.h.p.})^{\frac{1}{2}}\,H_s^{-\frac{5}{4}}\,\rho_s^{\frac{1}{2}} = \cdot 0126\,K_q^{\frac{1}{2}}\,K_s^{-\frac{3}{4}} \quad . \quad (13)$$

An example will best explain the method. Suppose that 2,000 c.f.m. of standard air ($\rho_s = 1$) is required at 0·5 in. fan static pressure, and suppose that it has been decided to use a propeller type fan of the family defined by fig. 2 and fig. 3, and to operate at the maximum obtainable static efficiency. From fig. 3 the specific diameter at maximum efficiency is 0·023, whence from equation (11) D equals 1·22 feet. Similarly, the specific speed at maximum efficiency is 135,000 and substitution in equation (12) gives $N = 1{,}790$ r.p.m.

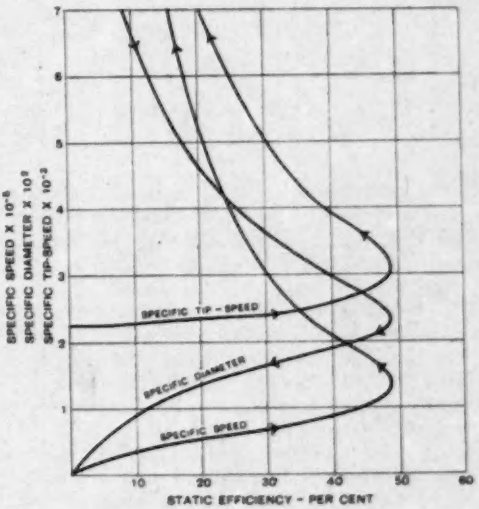

Fig. 3. Specific speed, diameter and tip-speed characteristics of the family of fans defined by fig. 2.

The method can also be employed when either the diameter or the speed are determined by considerations other than maximum efficiency. For instance, if it is necessary in

the example to use a 12 in. diameter fan, the specific diameter becomes 0·0188 and the static efficiency from fig. 3 is 40 per cent; at this efficiency the specific speed is 206,000 (note that corresponding branches of the curves of fig. 3 are indicated by arrows) giving 2,740 r.p.m. As a further instance the speed may be fixed at 1,400 r.p.m. by the selection of an electric driving motor, when the diameter will be found to be 1·40 feet and the efficiency 46 per cent. Tip-speed may become the controlling factor in cases where noise or mechanical strength are important.

The method can be further extended by plotting specific curves for a number of different types of fan on the same efficiency base. It is then possible to select the type giving the highest efficiency under such limitations of diameter or speed as may exist.

In spite of all these possibilities, the method appears to be very seldom used. The labour of constructing the curves is considerable, and is not repaid by ready reference in use, as a perusal of equations (10) to (13) will confirm. It may be remarked that the latter defect might be overcome by converting the ordinates of fig. 3 to a logarithmic scale and by adding alignment charts on the left-hand side, calibrated in terms of D, N, Q and H_s.

THE CHART AND CURSOR METHOD.

The writer's system, which is now to be described, is intended to solve without the necessity for any calculation, both performance prediction and fan selection problems. It employs for this purpose a logarithmically divided ground chart common to all types of fan and covering as wide a range as may be desired of Q, H_s, D and N.

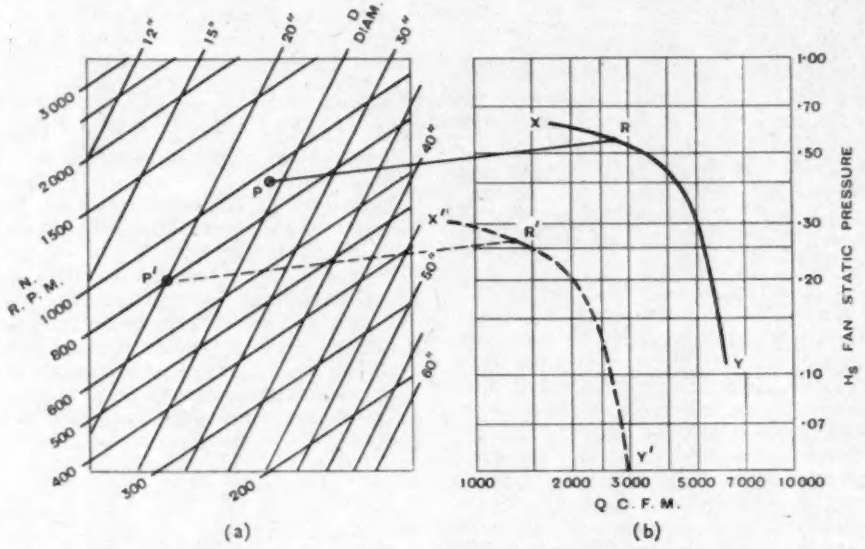

Fig. 4. Development of the logarithmically divided ground-chart showing the fan field (a) and the duty field (b).

Over this ground chart moves a sheet of transparent material, the "cursor," on which is drawn a curve characteristic of a particular family of fans, such as that defined by fig. 2. Other information relative to the family, such as efficiency, may also be recorded on the cursor, while one cursor may carry the characteristics of several different types or of one type under different conditions.

The development of the ground chart may be explained by reference to fig. 4 in which (*a*) shows a logarithmically divided field, any point on which defines a particular fan by its diameter D and speed N, while (*b*) is a similar field on which the duty point (Q, H_s) may be located. A full-line curve XY has been drawn on the duty field (*b*) and on comparing this with fig. 1 it will be seen to record the performance of the 24 inch 920 r.p.m. fan given

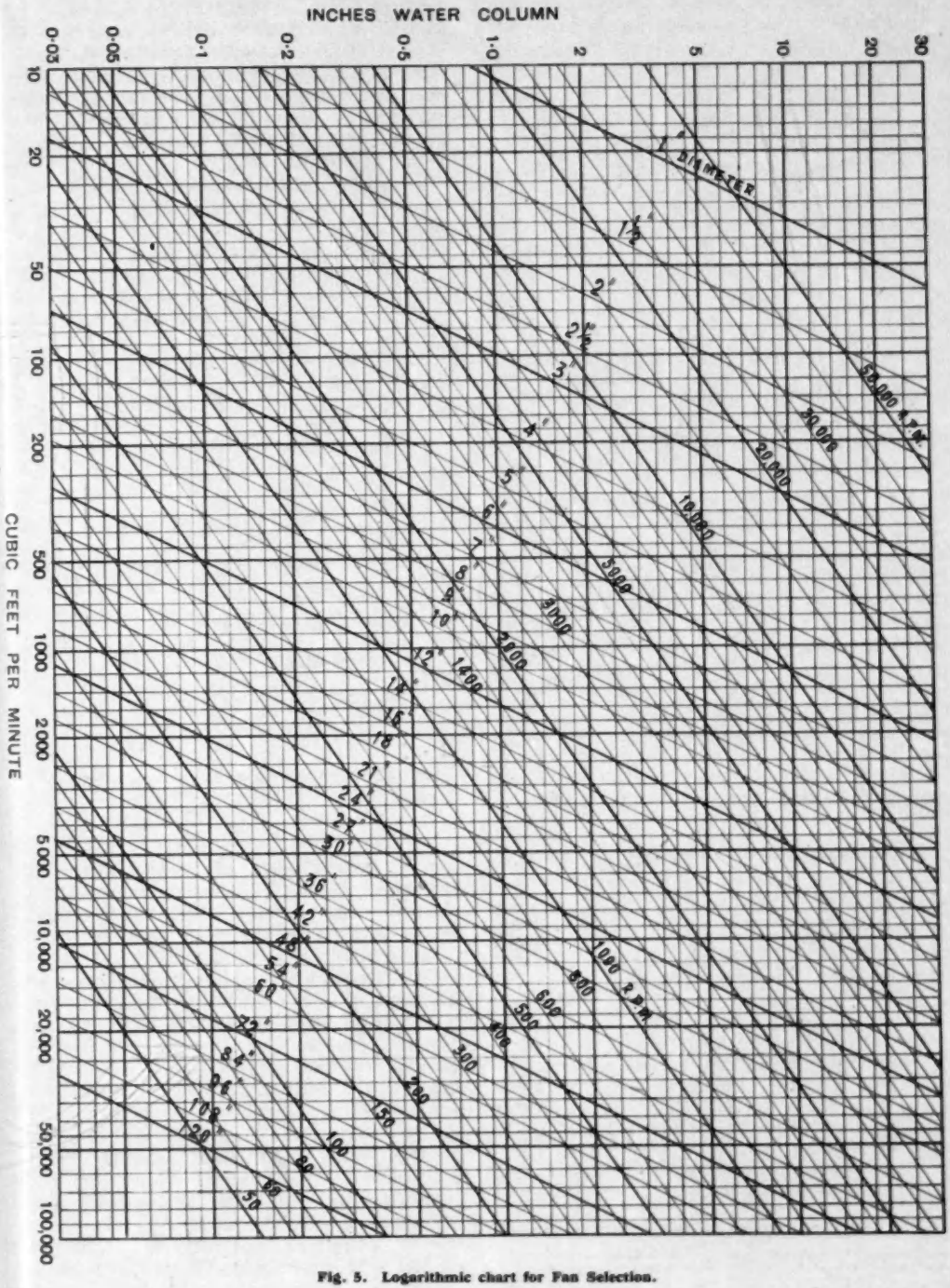

Fig. 5. Logarithmic chart for Fan Selection.

therein. Also the point P has been entered on the fan field (a) defining a 24 inch 920 r.p.m. fan.

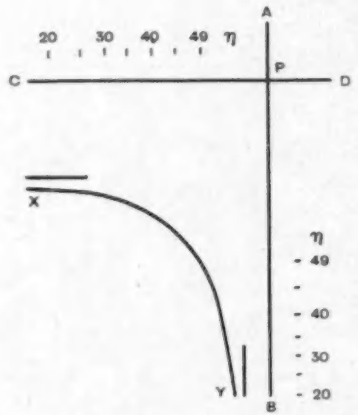

Fig. 6. Cursor for use with fig. 5 giving characteristics of fans similar to those in fig. 2.

The logarithmic scales and inclinations of the lines of constant D, N, Q and H_s on the two fields have been adjusted so that, on the horizontal axis, one decade (*e.g.*, 300 to 3,000) of N equals in length one decade of D and two decades of Q, while on the vertical axis one decade of D equals three decades of N and four decades of H_s.

The point R represents one possible duty of the fan defined by P; if two other points P^1 and R^1 are taken such that $P^1 R^1$ is equal and parallel to PR, it can easily be shown from equations (1) and (2) together with the above scale relations that R^1 will be a possible duty of the fan defined by P^1. By extending this construction, the whole performance of the fan P^1 can be predicted from the dotted curve X^1Y^1 which is similar to the full line curve XY but displaced from it by a distance equal and parallel to PP^1.

In practice, the fan field and duty field are superimposed as in the ground chart of fig. 5, the curve XY is drawn on a transparent cursor as in fig. 6, and the point P is located on this cursor in correct relationship to XY by the intersection of two lines, AB and CD, as shown. As this cursor is moved over the

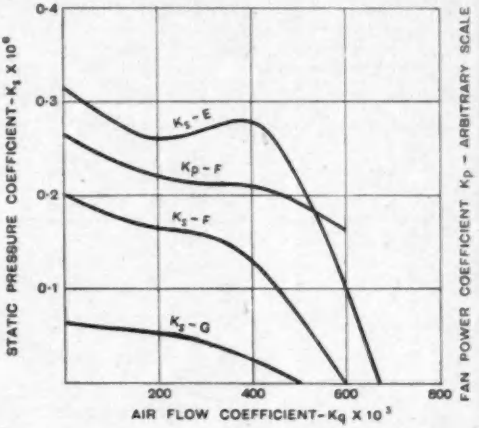

Fig. 8. Typical characteristics of axial-flow fans.
E—20 blades; hub-diameter ratio 0.7.
F—10 blades; hub-diameter ratio 0.5.
G—4 blades; hub-diameter ratio 0.3.

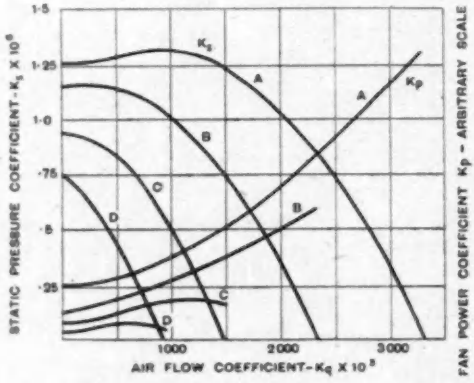

Fig. 7. Typical characteristics of general-purpose centrifugal fans.
A—Forward curve.
B—Radial curve.
C—Partial backward curve.
D—Full backward curve.

ground chart keeping AB parallel to the H_s axis and CD to the Q axis, the fan whose diameter and speed are located under P will always have the performance defined by the Q and H_s values under the curve XY.

This represents the complete solution of the performance prediction problem. The same cursor may be used to solve the fan selection problem thus: rotate the cursor through 180° so that B comes to the top and C to the right hand side; now place the intersection P over the required duty point (Q, H_s) keeping BA and DC parallel to the H_s and Q axes; the points under the curve YX now define on the ground chart the diameters and speeds of the range of fans which will give the required duty.

It is possible to draw a series of constant air horse-power lines on the ground chart

sloping up to the left at 45° but in practice these add too much to the congestion of the chart and it is better to calculate a.h.p. from equation (5). A scale of fan efficiency can be included on the cursor as in fig. 6,

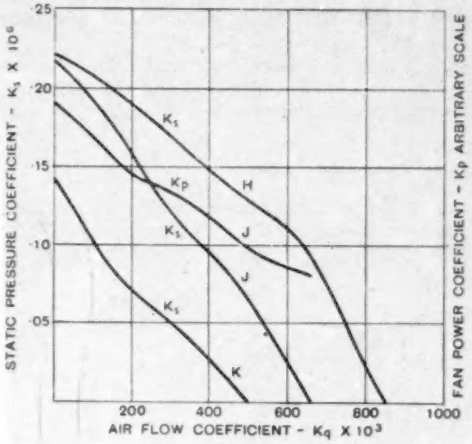

Fig. 9. Typical characteristics of propeller-type fans.
H—Heavy duty fan ; four broad blades ; 30° pitch angle.
J—Medium duty fan ; six medium blades ; 25° pitch angle.
K—Light duty fan ; four narrow blades ; 20° pitch angle.

and is so divided that the appropriate efficiency value is found above or to the right of each point on the fan characteristic *X Y*, or below and to the left when the cursor is reversed for fan selection.

Cursors may be drawn for total fan head and total efficiency in place of the static values and used over the same ground chart. An interesting application relates to noise level, which, with some fan types, is found to vary exponentially with the peripheral speed, the noise energy exponent being between six and seven. It is then possible to add a vertical scale of phons to the ground chart while a scale of *db.* corrections appears on the cursor in the same relationship to the characteristic curve as the efficiency values.

The ground chart of fig. 5 covers a very wide range, and it is often more convenient to construct a chart on a larger scale to cover that part of the area which is of direct value to the user. Once the ground chart has been drawn, any number of cursors may be simply produced direct on to ordinary tracing cloth from test or catalogue data. The cloth is placed over the ground chart with the intersection over the diameter and speed of the fan whose performance is being recorded, and the test points plotted over the corresponding values of Q and H, on the ground chart. In the case of catalogue data a check at several different diameters will reveal whether the series conforms to equations (1) and (2), *i.e.*, whether the fans are geometrically similar.

TYPICAL PERFORMANCE DATA.

A series of fan characteristic curves is presented in figs. 7, 8, 9 and 10 in illustration of the range available for selection and to facilitate direct comparison between the types. In these curves, the coefficients K_q and K_s have been multiplied by 10^3 and 10^6 respectively, so that the data may be more readily visualised, being numerically correct for a 12 in. diameter impellor running at 1,000 r.p.m. Fig. 11 shows these curves transferred to the logarithmic chart basis, and if they be copied on to a transparent cursor they may be used for ready reference in conjunction with fig. 5.

Fan horse-power coefficients have been included on figs. 7 to 10 for the purpose of showing the manner in which the power consumption varies with the quantity of air passing. These curves illustrate the well-known distinction in this respect between forward-curve fans, backward-curve fans and axial flow fans. The power curves are drawn to an arbitrary scale ; it would be misleading to assign efficiency values to the various types since the variation between different designs of

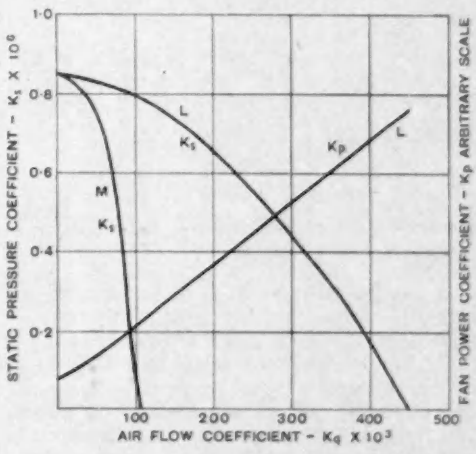

Fig. 10.—Typical characteristics of high-pressure blowers.
L—Discharge nozzle diameter one-third impellor diameter.
M—Discharge nozzle diameter one-sixth impellor diameter.

the same type is wider than the variation from type to type.

A few remarks on some of the types may not be out of place. While there is no accepted practice in the matter, the writer prefers to reserve the term "axial flow fans" for those (usually, but not necessarily, having aerofoil section blades) in which the air is constrained to travel in an axial (or more strictly helical) direction through the impellor by a close-fitting cylindrical casing. The title "propeller fan" can then be used for impellors designed to operate in a circular hole in a wall or diaphragm. It is not generally recognised that fans of this class, although low in cost, can be made with reasonably high efficiency, particularly near the high volume end of the characteristic, if the blades are carefully shaped to co-operate with the airflow pattern natural to a circular orifice.

In the centrifugal category the data given is for the general purpose type, employing the usual "snail" casing for velocity conversion. The terms "forward-curve" and "backward-curve" refer, of course, to the inclination of the trailing (outer) edge of each blade, relative to the direction of rotation. From these axially-long and radially-shallow bladed general purpose fans to the short, deep bladed turbo-compressor runner there is a wide range of possible designs of which the pressure blowers of fig. 10 are two. If the inner end of each blade is extended to meet the air flowing axially into the eye of the fan and so shaped as to exercise a screw-fan effect at this point (as typically in superchargers) the fan is sometimes termed "mixed flow" but the effect on specific performance is not great.

CONCLUSION.

It is hoped that the foregoing survey will prove of value to designers approaching the subject of fans for the first time or having to deal with applications outside the range with which they are familiar. It appears probable that the method described, in which a cursor is moved over a logarithmically divided field, has applications to other problems in which relationships between powers of the variables are combined with a form of variation not capable of mathematical expression. So far as the writer is aware, the principle is an original one.

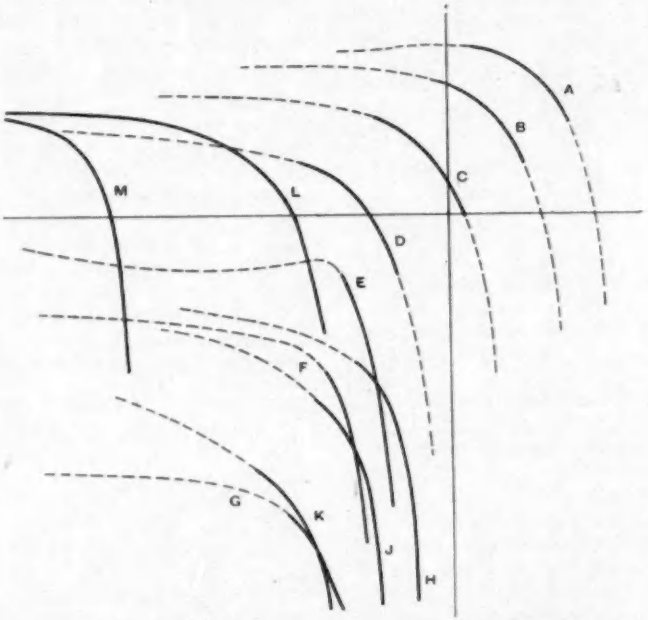

Fig. 11. Cursor for use with fig. 5. The fans are those referred to by the same letter in figs. 7 to 10. The full line portions of each curve represent the best operating ranges.

Rotating Fields in Polyphase Machines

By R. G. JAKEMAN, D.Sc., M.I.E.E.,

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THE theory of the production of rotating fields from polyphase currents has been discussed by many writers in the past 40 years or more.[1, 2, 3, 4] The treatment has been mathematical and the results obtained have not always been immediately obvious, especially with regard to the discrimination between time and space functions. In this article, the principles of the theory are explained again and a simple rule is obtained for determining the speeds and directions of rotation of the various harmonics.

Three phase Rotating Fields.

Considering first a 3 phase system, it is well known that a 3 phase winding supplied with a 3 phase current produces a rotating field. In fact, this is basic to the operation of 3 phase machines. The current in each phase by itself produces a pulsating m.m.f., but the combination of m.m.f.'s of the 3 phases, which are displaced from each other by 120 electrical degrees in space, produces a rotating m.m.f., the currents being displaced from each other by 120 electrical degrees in time.

The m.m.f. of each phase is distributed over the pole-pitch in accordance with the arrangement of the winding. Assume the distribution is sinusoidal. This is actually impossible with a 3 phase winding, but it is a close approximation and serves as an introduction to the mathematical treatment (see Appendix 3). Referring to fig. 1,

$$f_x = f \cos \frac{x}{\tau} \pi \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where f_x is the m.m.f. at a distance x from the centre of the pole, f is the m.m.f. at the centre of the pole and τ is the pole-pitch.

In addition to the variation of f_x in space over the pole-pitch, every ordinate of the sine-wave of distribution (fig. 1) varies with time, since it is proportional to the current at any instant. Assuming that the current varies sinusoidally, we have—

$$\begin{aligned} f &= F \cos \omega t \quad . \quad . \quad . \quad . \quad . \quad (2) \\ f_x &= F_x \cos \omega t \end{aligned}$$

and so on for every ordinate, where

ω = 2π multiplied by frequency = $2\pi c$

Equation (1) then becomes:

$$f_x = F \cos \omega t \cos \frac{x}{\tau} \pi$$

which gives the m.m.f. at a point x on the periphery of the stator, produced by the current in one phase.

Calling this phase A, and assuming a phase sequence A.B.C., the current in phase B reaches its maximum 120 electrical degrees in time after that in phase A, and similarly 120 degrees later still in phase C.

Equation (2) for the 3 phases then becomes:

Phase A $f_a = F \cos \omega t$
Phase B $f_b = F \cos (\omega t - 120°)$
Phase C $f_c = F \cos (\omega t - 240°)$

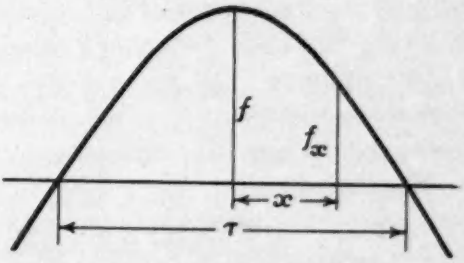


Fig. 1.—Hypothetical sine wave distribution.

Similarly, the 3 phases are displaced by 120 electrical degrees round the periphery, so that the m.m.f.'s at a distance x from the centre of phase A produced by the 3 phases are (Equation (1))

Phase A $f_{xa} = f_a \cos \frac{x}{\tau}\pi$

Phase B $f_{xb} = f_b \cos\left(\frac{x}{\tau}\pi - 120°\right)$

Phase C $f_{xc} = f_c \cos\left(\frac{x}{\tau}\pi - 240°\right)$

The resultant m.m.f. at a point x is the sum of the individual m.m.f.'s of the 3 phases and becomes :

$$F \cos \omega t \cos \frac{x}{\tau}\pi$$

$$+ F \cos (\omega t - 120°) \cos\left(\frac{x}{\tau}\pi - 120°\right)$$

$$+ F \cos (\omega t - 240°) \cos\left(\frac{x}{\tau}\pi - 240°\right)$$

This resolves into

$$\tfrac{1}{2} F\left[\cos\left(\omega t + \frac{x}{\tau}\pi\right) + \cos\left(\omega t - \frac{x}{\tau}\pi\right)\right]$$

$$+\tfrac{1}{2} F\left[\cos\left(\omega t + \frac{x}{\tau}\pi - 240°\right) + \cos\left(\omega t - \frac{x}{\tau}\pi\right)\right]$$

$$+\tfrac{1}{2} F\left[\cos\left(\omega t + \frac{x}{\tau}\pi - 480°\right) + \cos\left(\omega t - \frac{x}{\tau}\pi\right)\right]$$

The left-hand terms of this expression represent 3 equal vectors at 120 degrees to each other and therefore add up to zero.

The resultant m.m.f. at a point x is therefore :

$$\frac{3}{2} F \cos\left(\omega t - \frac{x}{\tau}\pi\right) \quad . \quad . \quad . \quad . \quad (3)$$

which shows that at any point x the m.m.f. varies sinusoidally at the same frequency as the current (see Equation (2)), and that the time-phase of the m.m.f. varies from point to point.

Now consider that the point x, instead of being stationary, rotates at an angular velocity ω. Then $\frac{x}{\tau}\pi/t = \omega$, or $\frac{x}{\tau}\pi = \omega t$. It follows from Equation (3) that the resultant m.m.f. at a point which is rotating at an angular velocity ω is $\frac{3}{2}F$, which is a constant quantity.

In other words, the resultant m.m.f. can be considered to be a rotating m.m.f. Its angular velocity is ω, so that the time taken to pass over 2 poles is the same as the time of a complete cycle of current. That is to say, the frequency of the rotating m.m.f. is the same as the frequency of the supply current. The direction of rotation is the same as the phase sequence, since the sign of $\frac{x}{\tau}\pi$ is the same as that of ωt.

Non-sinusoidal Waves.

In the above it has been assumed that both the current wave (in time) and the distribution wave (in space) are pure sine waves. In actual practice, harmonics are likely to occur in the former and always appear in the latter.

The actual harmonics in the distribution wave depend definitely on the distribution of the winding, and the more common types of winding are dealt with in Appendix 3. At present, it is assumed that any harmonics may be present, so that a general solution may be obtained. For the sake of simplicity, it is also assumed that both the current half-waves and distribution half-waves are symmetrical about a vertical axis, so that no sine terms appear. It is shown in Appendix 5 that this has no effect on the argument.

The general expression for the m.m.f. in phase A at a fixed point x, is :

$$F(\cos \omega t + a_2 \cos 2\omega t + a_3 \cos 3\omega t + \cdots\cdots)$$

$$(\cos \frac{x}{\tau}\pi + b_2 \cos \frac{2x}{\tau}\pi + b_3 \cos \frac{3x}{\tau}\pi + \cdots\cdots)$$

which resolves into

$$\tfrac{1}{2}F\left[\cos\left(\omega t + \frac{x}{\tau}\pi\right) + \cos\left(\omega t - \frac{x}{\tau}\pi\right)\right.$$

$$+ b_2 \cos\left(\omega t + \frac{2x}{\tau}\pi\right) + b_2 \cos\left(\omega t - \frac{2x}{\tau}\pi\right)$$

$$+ \cdots\cdots$$

$$+ a_2 \cos\left(2\omega t + \frac{x}{\tau}\pi\right) + a_2 \cos\left(2\omega t - \frac{x}{\tau}\pi\right)$$

$$+ a_2 b_2 \cos\left(2\omega t + \frac{2x}{\tau}\pi\right) + a_2 b_2 \cos$$

$$\left.\left(2\omega t - \frac{2x}{\tau}\pi\right) + \cdots\cdots\right]$$

It will be seen from this that the combination of any harmonic in the one wave with any harmonic in the other must be considered.

As a simple example, take the case of a 3 phase winding with a fifth harmonic in the current wave and a sine distribution of m.m.f. The m.m.f. of phase A at point x is :

$$F\left(\cos \omega t + a_5 \cos 5\omega t\right) \cos \frac{x}{\tau}\pi$$

$$= F \cos \omega t \cos \frac{x}{\tau}\pi + a_5 F \cos 5\omega t \cos \frac{x}{\tau}\pi$$

The first term refers to the fundamentals and has already been dealt with. The second term resolves into :

$$\tfrac{1}{2} a_5 F\left[\cos\left(5\omega t + \frac{x}{\tau}\pi\right) + \cos\left(5\omega t - \frac{x}{\tau}\pi\right)\right]$$

and this becomes for the other 2 phases :

$$\tfrac{1}{2}\,a_5\,F\Big[\cos\Big\{5\Big(\omega t-120^\circ\Big)+\Big(\frac{x}{\tau}\pi-120^\circ\Big)\Big\}+\cos\Big\{5\Big(\omega t-120^\circ\Big)-\Big(\frac{x}{\tau}\pi-120^\circ\Big)\Big\}\Big]$$

and

$$\tfrac{1}{2}\,a_5\,F\Big[\cos\Big\{5\Big(\omega t-240^\circ\Big)+\Big(\frac{x}{\tau}\pi-240^\circ\Big)\Big\}+\cos\Big\{5\Big(\omega t-240^\circ\Big)-\Big(\frac{x}{\tau}\pi-240^\circ\Big)\Big\}\Big]$$

Summing for all 3 phases, we have :

$$\tfrac{1}{2}\,a_5\,F\Big[\cos\Big(5\,\omega t+\frac{x}{\tau}\pi\Big)+\cos\Big(5\,\omega t-\frac{x}{\tau}\pi\Big)+\cos\Big(5\,\omega t+\frac{x}{\tau}\pi-720^\circ\Big)+\cos\Big(5\,\omega t-\frac{x}{\tau}\pi-480^\circ\Big)+\cos\Big(5\,\omega t+\frac{x}{\tau}\pi-1440^\circ\Big)+\cos\Big(5\,\omega t-\frac{x}{\tau}\pi-960^\circ\Big)\Big]$$

Here the right hand terms represent vectors at 120 degs. and add up to zero. The left hand terms are in phase.

The resultant m.m.f. at a fixed point x due to the combination of the fifth harmonic of current with the fundamental of distribution is :

$$\frac{3}{2}\,a_5\,F\cos\Big(5\,\omega t+\frac{x}{\tau}\pi\Big)$$

Using the same argument as for the fundamentals, we find that this m.m.f. is constant when $\frac{x}{\tau}\pi = -5\,\omega t$, which means that a rotating m.m.f. is produced in the opposite direction to the phase sequence and at 5 times the frequency.

Taking another example for comparison, consider a 3 phase winding with a sinusoidal current and a distribution wave containing a 5th harmonic.

The m.m.f. of phase A at point x is :

$$F\cos\omega t\Big(\cos\frac{x}{\tau}\pi+b_5\cos\frac{5x}{\tau}\pi\Big)$$

The second term for all 3 phases resolves into :

$$\tfrac{1}{2}\,b_5\,F\Big[\cos\Big(\omega t+\frac{5x}{\tau}\pi\Big)+\cos\Big(\omega t-\frac{5x}{\tau}\pi\Big)+\cos\Big(\omega t+\frac{5x}{\tau}\pi-720^\circ\Big)+\cos\Big(\omega t-\frac{5x}{\tau}\pi+480^\circ\Big)+\cos\Big(\omega t+\frac{5x}{\tau}\pi-1440^\circ\Big)+\cos\Big(\omega t-\frac{5x}{\tau}\pi+960^\circ\Big)\Big]$$

As before, the right hand terms add up to zero and the left hand terms are in phase. The resultant m.m.f. at a fixed point x due to the combination of the fundamental of current with a 5th harmonic of distribution is :

$$\frac{3}{2}\,b_5\,F\cos\Big(\omega t+\frac{5x}{\tau}\pi\Big)$$

This is constant when $\frac{x}{\tau}\pi = -\frac{1}{5}\,\omega t$ so that a rotating field is produced in the opposite direction to the phase sequence and at 1/5 the frequency.

General method for 3 phase windings.

The phase rotation for any combination of harmonics can be worked out in the same way as above, but the work involved would be rather tedious. A simpler method can be found by examination of the expressions.

Consider the combination of a n_1^{th} harmonic of current with a n_2^{th} harmonic of distribution in a 3 phase winding.

The resultant m.m.f. at point x is :

$$\tfrac{1}{2}\,a_n\,b_n\,F\Big[\cos\Big(n_1\,\omega t+n_2\frac{x}{\tau}\pi\Big)+\cos\Big(n_1\,\omega t-n_2\frac{x}{\tau}\pi\Big)+\cos\Big\{n_1\omega t+n_2\frac{x}{\tau}\pi-\Big(n_1+n_2\Big)120^\circ\Big\}+\cos\Big\{n_1\omega t-n_2\frac{x}{\tau}\pi-\Big(n_1-n_2\Big)120^\circ\Big\}+\cos\Big\{n_1\omega t+n_2\frac{x}{\tau}\pi-\Big(n_1+n_2\Big)240^\circ\Big\}+\cos\Big\{n_1\,\omega t-n_2\frac{x}{\tau}\pi-\Big(n_1-n_2\Big)240^\circ\Big\}\Big]$$

Dealing first with the left hand terms, if $(n_1 + n_2)\,120^\circ$ is a multiple of 360°, the 3 terms are in phase. Using the same argument as before, $\frac{x}{\tau}\pi = -\frac{n_1}{n_2}\,\omega t$, so that the rotating m.m.f. is in the opposite direction to the phase sequence and at $\frac{n_1}{n_2}$ times the frequency.

Similarly for the right hand terms, if $(n_1 - n_2)\,120^\circ$ is a multiple of 360°, $\frac{x}{\tau}\pi = \frac{n_1}{n_2}\,\omega t$ and the rotating field is in the same direction as the phase sequence and at $\frac{n_1}{n_2}$ times the frequency.

It follows from this that a rotating field is produced in a 3 phase winding if $n_1 + n_2 = 3d$, or $n_1 - n_2 = 3d$, where d is any integer, positive or negative, or zero. In the former case,

the rotation is opposite the phase sequence and in the latter in the same direction. In both cases, the frequency is $\frac{n_1}{n_2}$ times the supply frequency.

If neither expression is satisfied, no rotating m.m.f. is produced.

If both expressions are satisfied, two rotating m.m.f.'s are produced, one in either direction. These combine to produce a single stationary pulsating m.m.f. (See Appendix 1.)

Any number of phases.

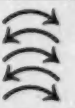
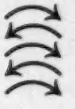
These results can now be extended to windings with any number of phases (see Appendix 2) and it is found that for an m-phase winding, a rotating m.m.f. is produced if $n_1 + n_2 = md$ or $n_1 - n_2 = md$, where d is any integer, positive or negative, or zero.

The general rules are that if $n_1 + n_2 = md$, the rotating m.m.f. is in the opposite direction to the phase sequence. If $n_1 - n_2 = md$, the rotating m.m.f. is in the same direction as the

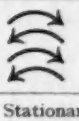
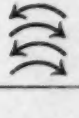
3 wire 2 phase (incomplete 4 phase). $m = 4$

Harmonics Current n_1	Distribution n_2	$n_1 + n_2$	$n_1 - n_2$	Direction	Frequency
1	1	2	**0**	↻	+ c
	2	3	− 1	Stationary	−
	3	**4**	− 2	↺	− ½c
	4	5	− 3	Stationary	−
	5	6	− **4**	↻	+ ¼c
	6	7	− 5	Stationary	−
	7	**8**	− 6	↺	− ⅐c
2	1	3	1	Stationary	−
	2	**4**	**0**	Stationary	−
	3	5	− 1	Stationary	−
	5	7	− 3	Stationary	−
	6	**8**	− **4**	Stationary	−
	7	9	− 5	Stationary	−
3	1	**4**	2	↺	− 3c
	2	5	1	Stationary	−
	3	6	**0**	↻	+ c
	4	7	− 1	Stationary	−
	5	**8**	− 2	↺	− ⅜c
	6	9	− 3	Stationary	−
	7	10	− **4**	↻	+ ⅜c
4	1	5	3	Stationary	−
	3	7	1	Stationary	−
	4	**8**	**0**	Stationary	−
	5	9	− 1	Stationary	−
	7	11	− 3	Stationary	−
5	1	6	**4**	↻	+ 5c
	2	7	3	Stationary	−
	3	**8**	2	↺	− ⅔c
	4	9	1	Stationary	−
	5	10	**0**	↻	+ c
	6	11	− 1	Stationary	−
	7	**12**	− 2	↺	− ⅖c
6	1	7	5	Stationary	−
	2	**8**	**4**	Stationary	−
	3	9	3	Stationary	−
	5	11	1	Stationary	−
	6	**12**	**0**	Stationary	−
	7	13	− 1	Stationary	−
7	1	**8**	6	↺	− 7c
	2	9	5	Stationary	−
	3	10	**4**	↻	+ ⅞c
	4	**11**	3	Stationary	−
	5	**12**	2	↺	− ⅞c
	6	13	1	Stationary	−
	7	14	**0**	↻	+ c

3 phase. $m = 3$.

Harmonics: Current n_1	Harmonics: Distribution n_2	$n_1 + n_2$	$n_1 - n_2$	Direction	Frequency
1	1	2	**0**		+ c
	2	**3**	- 1		- $\frac{1}{2}$c
	4	5	- **3**		+ $\frac{1}{4}$c
	5	**6**	- 4		- $\frac{1}{5}$c
	7	8	- **6**		+ $\frac{1}{7}$c
2	1	**3**	1		- 2c
	2	4	**0**		+ c
	4	**6**	- 2		- $\frac{1}{2}$c
	5	7	- **3**		+ $\frac{1}{3}$c
	7	**9**	- 5		- $\frac{1}{7}$c
3	3	**6**	**0**	Stationary	-
	6	**9**	- **3**	Stationary	-
4	1	5	**3**		+4c
	2	**6**	2		- 2c
	4	8	**0**		+ c
	5	**9**	- 1		- $\frac{1}{2}$c
	7	11	- **3**		+ $\frac{1}{4}$c
5	1	**6**	4		- 5c
	2	7	**3**		+ $\frac{1}{3}$c
	4	**9**	1		- $\frac{1}{2}$c
	5	10	**0**		+ c
	7	**12**	- 2		- $\frac{1}{4}$c
6	3	**9**	**3**	Stationary	-
	6	**12**	**0**	Stationary	-
7	1	8	**6**		+7c
	2	**9**	5		- $\frac{1}{3}$c
	4	11	**3**		+ $\frac{1}{4}$c
	5	**12**	2		- $\frac{1}{5}$c
	7	14	**0**		+ c

4 phase. $m = 4$.

1	1	2	**0**		+ c
	3	**4**	- 2		- $\frac{1}{3}$c
	5	6	- **4**		+ $\frac{1}{5}$c
	7	**8**	- 6		- $\frac{1}{7}$c
2	2	**4**	**0**	Stationary	-
	6	**8**	- **4**	Stationary	-
3	1	**4**	2		- 3c
	3	6	**0**		+ c
	5	**8**	- 2		- $\frac{1}{3}$c
	7	10	- **4**		+ $\frac{1}{7}$c
4	4	**8**	**0**	Stationary	-
5	1	6	**4**		+5c
	3	**8**	2		- $\frac{1}{3}$c
	5	10	**0**		+ c
	7	**12**	- 2		- $\frac{1}{7}$c
6	2	**8**	**4**	Stationary	-
	6	**12**	**0**	Stationary	-
7	1	**8**	6		- 7c
	3	10	**4**		+ $\frac{1}{3}$c
	5	**12**	2		- $\frac{1}{5}$c
	7	14	**0**		+ c

phase sequence. In both cases, the frequency of the rotating m.m.f. is $\frac{n_1}{n_2}$ times the supply frequency.

If neither $(n_1 + n_2)$ nor $(n_1 - n_2) = md$, no resultant m.m.f. is produced by the combination of the n_1^{th} harmonic of current and the n_2^{th} harmonic of distribution.

If both $(n_1 + n_2)$ and $(n_1 - n_2)$ are multiples of m, two rotating m.m.f.'s are produced, one in either direction, which combine to produce a stationary pulsating m.m.f.

The above rules enable the phase rotation and frequency to be determined for any combination of harmonics for any number of phases. The only exception is the 3 wire 2 phase system which is in reality an incomplete 4 phase system. This is dealt with in Appendix 2.

The tables give the phase rotation and frequency for a number of combinations of harmonics and various numbers of phases. The combinations which give no resultant m.m.f. are omitted.

These tables include all harmonics up to the 7th, but it must be remembered that some of those shown may not be present in the distribution wave. The harmonics in the most usual windings can be found in Appendix 3.

Appendix 1.
Combination of two m.m.f.'s rotating in opposite directions at the same frequency.

Let the two m.m.f.'s be :

$$\tfrac{1}{2} F \cos\left(n_1 \omega t + n_2 \frac{x}{\tau} \pi\right)$$

and

$$\tfrac{1}{2} F \cos\left(n_1 \omega t - n_2 \frac{x}{\tau} \pi\right)$$

6 phase. $m = 6$

Harmonics Current n_1	Harmonics Distribution n_2	$n_1 + n_2$	$n_1 - n_2$	Direction	Frequency
1	1	2	**0**	↻↻	+ c
	5	**6**	− 4	↻↺	− $\frac{4}{5}$c
	7	8	− **6**	↺↺	+$\frac{6}{7}$c
2	2	4	**0**	↻↻	+ c
	4	**6**	− 2	↻↺	− $\frac{2}{3}$c
3	3	**6**	**0**	Stationary	-
4	2	**6**	2	↻↺	− 2c
	4	8	**0**	↻↻	+ c
5	1	**6**	4	↻↺	− 5c
	5	10	**0**	↻↻	+ c
	7	**12**	− 2	↺↺	− $\frac{2}{7}$c
6	6	**12**	**0**	Stationary	-
7	1	8	**6**	↻↺	+7c
	5	**12**	2	↻↻	− $\frac{7}{5}$c
	7	14	**0**	↺↺	+ c

12 phase. $m = 12$

1	1	2	**0**	↻	+ c
2	2	4	**0**	↻	+ c
3	3	6	**0**	↻	+ c
4	4	8	**0**	↻	+ c
5	5	10	**0**	↻↻	+ c
	7	**12**	− 2	↺↺	− $\frac{2}{7}$c
6	6	**12**	**0**	Stationary	-
7	5	**12**	2	↻↺	− $\frac{7}{5}$c
	7	14	**0**	↺↺	+ c

The sum of these is :

$$F \cos n_1 \omega t \cos n_2 \frac{x}{\tau} \pi$$

It will be seen from the initial treatment on p. 41, that this is a pulsating m.m.f. caused by the combination of an alternating m.m.f. $f = F \cos n_1 \omega t$ with a distribution $f_x = f \cos n_2 \frac{x}{\tau} \pi$.

Hence two equal m.m.f.'s rotating in opposite directions at the same frequency are equivalent to a stationary pulsating m.m.f.

Appendix 2.
Number of phases.

An m-phase winding is one in which the winding is divided into m equal parts displaced from each other by $2\pi/m$ electrical radians in space and supplied with m currents displaced from each other by $2\pi/m$ electrical radians in time.

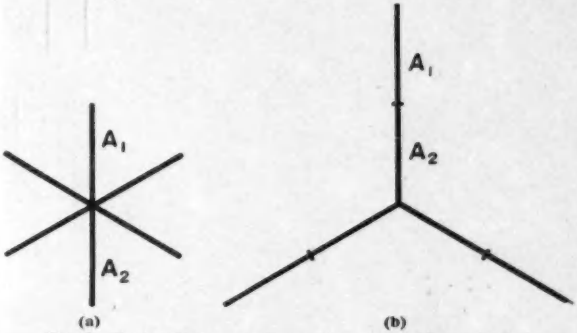


Fig. 2.—Vector diagrams of currents : (a)—6-phase winding. (b)—3-phase winding.

An elementary 3 phase winding consists of 3 parts, each spread over one-third of the double-pole-pitch and supplied with 3 currents at 120 degs. The usual 3 phase winding is divided into 6 parts, each spread over one-sixth of the double-pole-pitch, and opposite parts are connected in series. This is not a 6 phase winding, since only 3 currents at 120 degs. are supplied.

At first sight, it would appear that the 6 phase winding (fig. 2a) is identical with the 3 phase winding divided into 6 parts (fig. 2b) with respect to the currents flowing in the various parts. As far as the fundamental and odd harmonics in the current wave are concerned, this is the case, but a difference occurs for even harmonics.

In the 3 phase winding, the current is always the same in the parts A_1 and A_2. In the 6 phase winding, let the current in A_1 towards the neutral be :

$$C \cos \omega t + a_n C \cos n\omega t$$

Then the current in A_2 towards the neutral is :

$$C \cos (\omega t - 180°) + a_n C \cos n (\omega t - 180°)$$
$$= - C \cos \omega t + (-1)^n a_n C \cos n \omega t$$

The current in A_2 *away from* the neutral, *i.e.*, in phase with the current in A_1 *towards* the neutral, is $C \cos \omega t - (-1)^n a_n C \cos n \omega t$.

This shows that for the fundamental and odd harmonics, the current is the same in A_1 and A_2.

For the second harmonic we have :

in A_1 $C \cos \omega t + a_n C \cos 2 \omega t$

in A_2 $C \cos \omega t - a_n C \cos 2 \omega t$

which shows that the current is different in A_1 and A_2, whereas with the 3 phase winding, it is the same. Similarly for all even harmonics.

2 phase winding.

In the 2 phase winding, the phases are spaced at 90 electrical degrees and the currents are displaced by the same angle. It is therefore a 4 phase winding, since $2\pi/4 = 90$ degs.

The 3 wire, 2 phase winding is thus an incomplete 4 phase winding, two of the legs being omitted. On account of this, the rules given above (on p. 44) do not hold good, and rotating fields exist when neither $(n_1 + n_2)$ nor $(n_1 - n_2)$ are multiples of 4.

As an example, consider the combination of a 2nd harmonic in the current wave and the fundamental of the distribution wave. The m.m.f. is :

$$\tfrac{1}{2} a_2 F \Big[\cos \Big(2 \omega t + \frac{x}{\tau} \pi\Big) + \cos \Big(2 \omega t - \frac{x}{\tau} \pi\Big) + \cos \Big(2 \omega t + \frac{x}{\tau} \pi - 270°\Big) + \cos \Big(2 \omega t - \frac{x}{\tau} \pi - 90°\Big)\Big]$$

which resolves into

$$\sqrt{2}\, a_2 F \Big[\cos \Big(2 \omega t + \frac{x}{\tau} \pi + 45°\Big) + \cos \Big(2 \omega t - \frac{x}{\tau} \pi - 45°\Big)\Big]$$

This represents two rotating waves in opposite directions, which can be combined into a stationary wave.

An exception to this is when $(n_1 \pm n_2)\ 90°$ is an odd multiple of 180°.

Take as an example $n_1 = 2$ and $n_2 = 4$. The m.m.f. is

$$\tfrac{1}{2} a_2 b_4 F\Big[\cos\Big(2\omega t + \frac{4x}{\tau}\pi\Big) + \cos\Big(2\omega t - \frac{4x}{\tau}\pi\Big) + \cos\Big(2\omega t + \frac{4x}{\tau}\pi - 540°\Big) + \cos\Big(2\omega t - \frac{4x}{\tau}\pi - 180°\Big)\Big]$$

The left hand and right hand terms each add up to zero and there is no resultant m.m.f.

The rules for a 3 wire, 2 phase winding then become:

If $n_1 + n_2 = 4d$, the rotating m.m.f. is in the opposite direction to the phase sequence. If $n_1 - n_2 = 4d$, the rotating m.m.f. is in the same direction as the phase sequence.

If both $(n_1 + n_2)$ and $(n_1 - n_2) = 4d$, two rotating m.m.f.'s are produced, which combine to produce a stationary pulsating m.m.f.

If neither $(n_1 + n_2)$ nor $(n_1 - n_2) = 4d$, a stationary m.m.f. is produced, except when both $(n_1 + n_2)\ 90°$ and $(n_1 - n_2)\ 90°$ are odd multiples of 180°, when no resultant m.m.f. occurs.

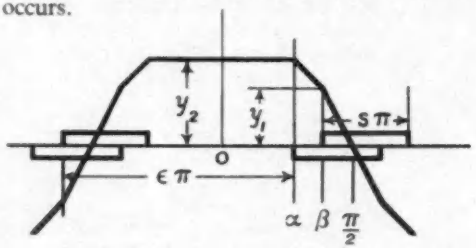


Fig. 3.—Distribution of short chorded winding where $\varepsilon + S > 1$

Appendix 3.

Harmonics in Distribution Curves.

The distribution of m.m.f. of one phase over the pole-pitch follows a geometric figure, which takes the form of a trapezium for a symmetrical full pitch winding. Actually, the sides of the trapezia are stepped due to the spacing of the winding in slots. These steps produce higher harmonics, but as they are usually of small amplitude they have been neglected.

For a short-chorded winding, the shape of the distribution curve is as shown in fig. 3. This can be analysed mathematically as indicated in the writer's previous article[5] and a general solution found for any number of phases and any amount of short-chording.

If the winding is entirely symmetrical, *i.e.*, if there are 2 coils per pole pair for each phase, there are no even harmonics.

Also, if angles are measured from the centre of the max. m.m.f., the half-waves are symmetrical about a vertical axis and there are no sine terms.

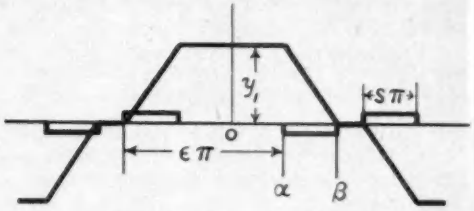


Fig. 4.—Distribution of short chorded winding where $\varepsilon + S < 1$

The curve is therefore expressed by:

$$f_x = f\Big(\cos\frac{x}{\tau}\pi + b_3\cos\frac{3x}{\tau}\pi + b_5\cos\frac{5x}{\tau}\pi + \cdots + b_n\cos\frac{nx}{\tau}\pi + \cdots\Big)$$

The coefficient for the n^{th} harmonic (odd values only) can be developed into:

$$b_n = \frac{4y_2}{\pi(\pi-\beta-\alpha)}\Big(\frac{\cos n\alpha + \cos n\beta}{n^2}\Big)$$

which resolves into

$$b_n = \frac{2\,Qui}{\pi^2}\Big(\frac{\cos n\alpha + \cos n\beta}{n^2}\Big)$$

where Q = number of slots per pole
u = number of conductors per slot.
i = instantaneous value of current.
α and β are shown in fig. 3.

The following table gives the values of α and β, expressed in radians, for various phase spreads and for any short-chording where ε represents the fractional chording, *e.g.*, for a 2/3rd pitch, $\varepsilon = 0{\cdot}667$.

Phase spread S	No. of phases	$\alpha = \left(\frac{\varepsilon}{2} - \frac{S}{2}\right)\pi$	$\beta = \left(1 - \frac{\varepsilon}{2} - \frac{S}{2}\right)\pi$
$S = \frac{1}{3}$	4	$\left(\frac{\varepsilon}{2} - \frac{1}{4}\right)\pi$	$\left(1 - \frac{\varepsilon}{2} - \frac{1}{4}\right)\pi$
$S = \frac{1}{4}$	3 or 6	$\left(\frac{\varepsilon}{2} - \frac{1}{6}\right)\pi$	$\left(1 - \frac{\varepsilon}{2} - \frac{1}{6}\right)\pi$
$S = \frac{1}{6}$	6 or 12	$\left(\frac{\varepsilon}{2} - \frac{1}{12}\right)\pi$	$\left(1 - \frac{\varepsilon}{2} - \frac{1}{12}\right)\pi$

It is also possible, especially with a large number of phases, for the short-chording to be such that the two portions of the winding belonging to the same pole do not overlap.

This is shown in fig. 4 and occurs when $(\varepsilon + S) \gtrless 1$.

In this case the coefficient for the n^{th} harmonic (odd values only) becomes:

$$b_n = \frac{4y_1}{\pi(\beta - \alpha)}\left(\frac{\cos n\alpha - \cos n\beta}{n^2}\right)$$

which resolves into

$$b_n = \frac{2\,Qui}{\pi^2}\left(\frac{\cos n\alpha - \cos n\beta}{n^2}\right)$$

where $\alpha = \left(\frac{\varepsilon}{2} - \frac{S}{2}\right)\pi$

$$\beta = \left(\frac{\varepsilon}{2} + \frac{S}{2}\right)\pi$$

A special case is a 3 phase winding with a 2/3rds spread and short-chording (see fig. 5). Here there is only one coil per phase per pole pair and the distribution is not symmetrical. Since the two halves of the curve are not images of each other, even harmonics are present. On the other hand, each half of the curve is symmetrical about a vertical axis, so that no sine terms appear.

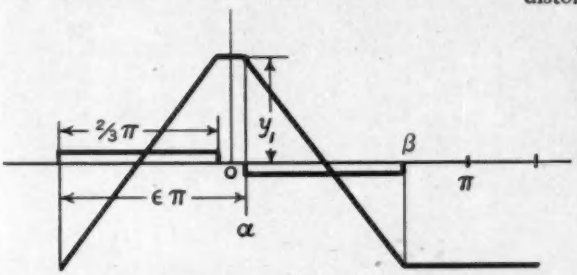


Fig. 5.—Distribution of short chorded winding with 2/3rds spread.

The wave is therefore represented by

$$f_x = f\left(\cos\frac{x}{\tau}\pi + b_2\cos\frac{2x}{\tau}\pi + b_3\cos\frac{3x}{\tau}\pi + \cdots + b_n\cos\frac{nx}{\tau}\pi + \cdots\right)$$

The coefficient for the n^{th} harmonic (odd and even values) becomes:

$$b_n = \frac{4y_1}{\pi(\beta - \alpha)}\left(\frac{\cos n\alpha - \cos n\beta}{n^2}\right)$$

which resolves into

$$b_n = \frac{2Qui}{\pi^2}\left(\frac{\cos n\alpha - \cos n\beta}{n^2}\right)$$

If ε, the short chording factor, is greater than or equal to the phase-spread of 2/3rds,

$$\alpha = \left(\frac{\varepsilon}{2} - \frac{1}{3}\right)\pi$$

$$\beta = \left(\frac{\varepsilon}{2} + \frac{1}{3}\right)\pi$$

If ε is less than 2/3rds

$$\alpha = \left(\frac{1}{3} - \frac{\varepsilon}{2}\right)\pi$$

$$\beta = \left(\frac{1}{3} + \frac{\varepsilon}{2}\right)\pi$$

Appendix 4.

Even harmonics.

The current wave in a purely A.C. network is usually symmetrical and contains no even harmonics. The addition of rectifying apparatus may add even harmonics to the wave.

Windings are usually symmetrical so that there are no even harmonics in the distribution curve. An exception is the short chorded 3 phase winding with 2/3rds spread as explained in Appendix 3. For the sake of completeness, even harmonics have been included in the Tables.

Appendix 5.

Distorted current waves.

Only symmetrical current waves with no sine terms have been considered up to the present. Actually the current wave may be distorted and be represented by:

$$f = F\left[\cos\left(\omega t + \theta_1\right) + b_3\cos\left(3\,\omega t + \theta_3\right) + \cdots\right]$$

Combining the fundamental of the current wave with the fundamental of the distribution we have:

$$f_x = F\cos\left(\omega t + \theta_1\right)\cos\frac{x}{\tau}\pi$$

The resultant m.m.f. at a point x for the 3 phases is then (see Eqn. (3))

$$\frac{3}{2}F\left(\cos\left(\omega t + \theta_1 - \frac{x}{\tau}\pi\right)\right)$$

Consider a point rotating at an angular velocity ω and let this point be at an angle $-\theta_1$, at time $t = 0$. Then we have $\left(\frac{x}{\tau}\pi - \theta_1\right) = \omega t$. The field at the rotating point has then the constant value $\frac{3}{2}F$ showing that a rotating field has been produced as before.

Harmonics can be worked out in the same way and it is seen that the presence of sine terms in the current wave do not affect the direction of rotation of the fields.

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Technical Literature.

A DIGEST OF RECENT BOOKS, ARTICLES AND PAPERS BY MEMBERS OF THE G.E.C. AND ITS ASSOCIATED COMPANIES.

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By A. S. Gladwin (Research Laboratories).

Wireless Engineer, 20, p. 540, November, 1943.

By modifying the values of the elements of a filter and/or by introducing new elements, band-pass filters may be made to behave like the original filter plus a perfect transformer. The conditions necessary to permit this transformation, and the limitations on the types of impedance arms, ratio of transformation and frequency range, are examined. A new equivalent circuit aids the analysis.

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By W. R. Stevens (Research Laboratories).

Trans. I.E.S., Vol. 8, p. 175, December, 1943.

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Jour. Photo. Inst., Vol. 83, p. 299, August, 1943.

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By R. O. Jenkins (Research Laboratories).

Reports on Progress in Physics, Vol. 9, 1942-43.

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Engineering, Vol. 156, p. 454, December 3rd, 1943.

A biographical account of the career, achievements and character of one of the outstanding engineer-scientists of our time.

THE COMPILATION OF TECHNICAL PAPERS AND LECTURES.

By W. Wilson (Witton Development Laboratory).

J. Inst. Inst. Eng., Vol. 53, Part II, pp. 279/89, August, 1943.

The process of preparing papers or lectures and their presentation to a technical audience are described. Such points as subject matter and construction, as well as notes on style and grammar, the use of illustrations and the manner of delivery are dealt with.

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